THE TRICKS OF LIGHT AND COLOUR

In this series

TOYS AND INVENTIONS

FUN WITH MECHANICS

ODDITIES OF HEAT

ODDITIES OF SOUND

THE MAGIC OF CHEMISTRY

HALF-HOURS WITH GEOLOGY

THE TRICKS OF LIGHT AND COLOUR

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AUTHOR'S NOTE

I HAVE been very happy writing this book.

I have tried to keep clear of subjects that are adequately dealt with in school textbooks, though I have adapted some things so as to make them suitable for home use.

I wish to acknowledge my indebtedness to my sons for their ungrudging and unfailing help. It has been pleasant to discuss dubious points with them, and indeed there are many in this tricky and elusive—and very fascinating—subject of light.

I wish to thank also the authors and publishers of two very charming books: *Light and Colour in the Open Air*, by M. Minnaert (Bell) and *Adaptive Coloration in Animals*, by Hugh Cott (Methuen).

CONTENTS

CHAPTER 1

HOW WE SEE

(Try to answer these questions first)

What is the retina?
In what direction do we see objects?
How does a sailor use landmarks?
Why is an astronomer a " super-range-finder "?
What is binocular vision?
Which is your dominant eye?
How do the eyes act as range-finders?
How does the stereoscope act?
How can we get a stereoscopic effect from a single picture?
How do artists get stereoscopic effects?
What is an anaglyph?
What is meant by "parallax "?
How is the parallax of stars measured?
How does a pinhole form an image?
Why are circles of light often seen under trees?
How is a pinhole camera for taking photographs made?
How does closeness affect apparent size?
What is the least distance of distinct vision?

WE look at a tree, and admire its sturdy trunk. We see the many colours of the foliage that seem never twice alike. We see! That is the amazing thing we so easily take for granted. We see—but how do we see? Why do we see?

It seems that light from the tree enters the eye, and forms an image on a little screen at the back of the eye

(Fig. 1); just as light entering a camera forms an image on a photographic film. The little screen at the back of the

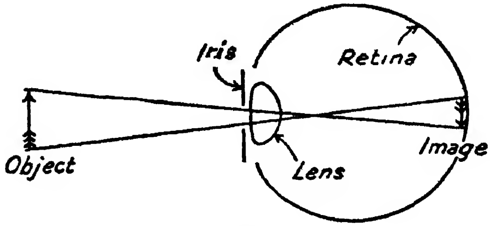


Fig. 1.

eye is called the *retina*. It is a sensitive screen containing a large number of nerve-endings; the nerves run back to the brain, and each carries a message telling the kind of light that has fallen on it. The brain reads the messages and fits them together, and so it interprets the picture on the retina, and we see the details of the tree.

We know that some people see far more than others. Their eyes may be very much the same, and there may be the same picture on the retinas of each; but that is not everything. It is the brain that interprets the picture; we have to learn to see. We have to teach ourselves to look closely, to examine, to compare, to think about what we see. And so we may learn to see as an artist, or a scientist, or a detective sees.

The Direction in which We See

Our eyes form a picture of the tree; and again that is not everything. They tell us where the tree is. Rays of light come to us from the tree, and we see the tree back along those rays. If the rays come from the left we see the tree to the left; if they come from the front we see the tree to the front. We are relying on the fact that light travels in straight lines. Light comes to our eyes in straight lines and we see the tree back along those straight lines. That is why the picture on the retina has to be

upside down and left to right, as indeed it is—just as the image in a camera is upside down and left to right.

Rays of light tell us a lot, but they do not always tell us the whole truth. Usually we can rely confidently on the fact that light travels in straight lines. But the rays may be bent, and they do not always politely inform us of the fact. We look at a mirror, and our eyes tell us that our face is behind the mirror. We are not deceived, because we know very well what is happening. Rays of light from the face fall on the mirror and are turned back; they reach the eyes from the mirror; we see the face back along the rays, and so it appears to be behind the mirror. We are so used to the phenomenon that we interpret it correctly. It is related of Narcissus that he was deceived by his reflection in the smooth surface of a pool. He believed implicitly what his eyes told him, and in trying to join the beautiful youth in the pool he came to an untimely end.

Indeed, it does not do to trust our eyes too readily. There is a tale of a Chinese lady who found a mirror among her husband's possessions. She looked in it and saw a picture of an angry, jealous woman, and she rebuked her husband for preferring such a woman to herself. The husband saw a portrait of a designing, sour-faced young man, and he was equally angry. At last they took the quarrel to the priest. "My children," said the priest, "you are both wrong. This is a portrait of a very holy man, and I will put it among the treasures of the temple."

A traveller in the desert may be fatally deceived by his eyes. Bent rays of light tell him that there are trees and pools of water in front of him; he sees them back along the final direction in which the rays reach him, and he hurries hopefully towards them. But it is all a mirage. The bend in the rays of light has deceived him, and he finds nothing but hot, empty desert.

Light in Straight Lines

Usually, however, we are not wrong in relying on the straight lines in which light travels. Almost at any time

we can see examples of these straight paths. The edges of shadows run out in straight lines; the edges of search-light beams are straight; the edges of beams of light pouring out through open doors at night are straight. Sometimes the setting sun sends beams of light through gaps in the clouds, and the edges of the beams are straight.

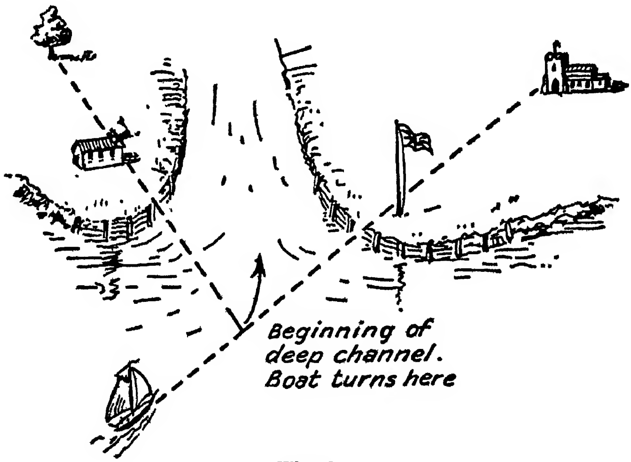


Fig. 2.

The men behind a searchlight can tell the direction of an aeroplane they pick up in the beam. They know that the light of the searchlight travels out in straight lines, and that light reflected from the aeroplane comes back in straight lines. The plane is straight out along the beam that picks it up.

The sailor who uses landmarks to find his exact position near the coast is doing a little exercise in practical geometry. He also relies on the straightness of light rays. He sees two objects, one exactly behind the other (Fig. 2), and he knows that he is somewhere on the straight line joining them. He turns and sails along this line, still keeping one object exactly behind the other. He looks out for

two other objects he knows about; and he sails on till he sees one of these objects exactly behind the other. He knows he is then at the spot where two lines cross, the lines joining two pairs of objects. The landmarks have enabled him to fix his position exactly.

Trees, towers, spires, flagstaffs, and other prominent objects may be used as landmarks for fixing positions near the coast. Landmarks are chosen so that when a sailor fixes his position by means of them he may know exactly how to steer. The marks may indicate a good fishing-ground, or they may tell the sailor how to find a deep channel that leads to a harbour.

Marksman and Surveyor

A marksman uses the straightness of light rays when he aims at a target. His " landmarks " are the sights on his gun or rifle. He turns the gun until the target is seen exactly behind both sights. He knows then that sights and target are in an exact straight line, and that the gun is pointing straight at the target. The sights do indeed serve another purpose that has nothing to do with the straightness of light rays. They enable the marksman to tilt up his gun or rifle at the correct angle, so that proper allowance is made for the fall of the bullet or shell while it is travelling from the gun to the target.

A surveyor is another of the many people who rely confidently on the straightness of rays of light. He uses this straightness when he is measuring the distances of distant objects and places. To begin with, he has to have a carefully measured base line; he can use this single measurement of length to find any number of distances adjoining the base line. He wants to find the distance of an object at C, some distance from his base line AB (Fig. 3). He fixes up his theodolite at A; the theodolite is a telescope that can be swung round on a graduated circle, and used to measure angles. He points the telescope at B; then he swings it round till it points at C; and so he measures the angle BAC. He carries the theodolite to

the other end of the measured base, and he uses it to measure the angle ABC. Now he knows the length of the base and the two angles at the base; he knows them because he has measured them. He can, if he likes, draw the triangle to scale, and so he can find the distances AC and BC. Or he can calculate these distances by using the trigonometrical ratios and formulae. As soon as he has found the lengths AC and BC he can use these lengths as bases for measuring other lengths; and so he can proceed step by step. But notice that what the theodolite actually measures is the angle between rays of light from B to A, and rays of light from C to A.

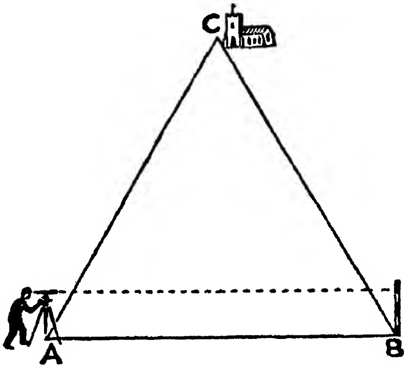


Fig. 3.

The Range-finder's Problem

The problem of the range-finder is essentially the same as that of the surveyor. He has to find the distances of targets from the points where guns are to be placed, and he follows much the same procedure as a surveyor. The essentials of a range-finder are a measured base line, and a means of measuring the angles between the base line and the distant target. When the sizes of the angles are known the distance can be calculated. It is of course a great advantage to have all the calculations done beforehand, so that the range-finder need only measure the angles, look at the table, and so find the range in a very short time.

The astronomer who measures the distance of a star is a sort of super-range-finder. The base he uses is the whole width of the earth's orbit, 186 million miles; and the angle he measures is the angle between the directions

of a telescope pointed at the star from opposite points on the orbit, at intervals of six months. This angle is a fraction of a second, which is itself 1/3600 of a degree. The astronomer relies on the straightness of light rays that have travelled billions of miles before reaching the earth. He has to be very sure of that straightness before starting to make his measurements.

No Seeing Round Corners

The straightness of light rays prevents us seeing round corners. The street-fighter, armed with Tommy gun, approaches a corner secure in his mind that he is hidden from possible enemies round the corner. Danger begins when he tries to go round the corner, so that rays of light from his body can reach the watching eyes of enemies waiting there.

In Fig. 4 anyone in the angle BCD is completely hidden from an enemy at A. An attacker can safely move up to the position E. But the moment he exposes himself beyond the line AB he is in danger of being seen, and liquidated.

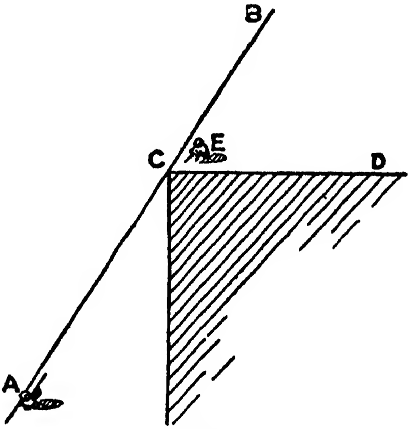


Fig. 4.

Seeing with Two Eyes

Our two eyes enable us, to a small extent, to get over the difficulty of seeing round corners. Let us hold a matchbox about a foot away from the eyes, with one of the narrow ends toward the eyes (Fig. 5). We close the left eye, and we find that with the right eye only we can see a little round to the right. We close the right eye, and we find that we can see a little round to the left.

There is a distinct difference between what the right eye sees and what the left eye sees. We move the box closer to the eyes, and we find that the difference between the two views is greatly increased; we move it farther away, and we find that the difference is less. If the box were moved farther away still the difference would become less and less, until it ceased to be noticeable.

Fig. 5.

Now it is just this difference in the appearance of objects when seen by the two eyes that gives them the effect of solidity. Our eyes always squint slightly inward, so that we see the two views in the same place; the brain puts the two views together and so obtains the effect of solidity. In near objects there is a considerable difference between the two views, and a strong effect of solidity. The difference, as we have seen, decreases with the distance of the object. That is why near objects appear more solid than distant ones, and why backgrounds appear flat. The flatness of backgrounds is a quality that every artist is aware of, and one that may be observed by anyone, artist or not. Great distance gives the globular sun and moon the appearance of flat disks.

Looking through the Hand

The difference between the two views, by left eye and right, is amusingly illustrated by the following simple experiment. Roll a piece of paper into a loose tube an inch or so across, hold it close up to the left eye, and look through it. Hold the right hand, flat out, touching the tube and a few inches from the right eye. Apparently we see through a hole in the right hand. That is what our eyes tell us, though we know quite well that it is not true. Actually the left eye sees the hole, which is the end of the tube; the right eye sees the hand. The brain puts the two pictures together to give an odd effect. Instead of using a paper tube, by the way, we can fold the fingers of the left hand so as to make a sort of tube.

Here is another odd effect of the same kind. Sit with the knees apart, and an elbow resting on each; hold the palms of the hands upward, and let the tips of the fingers touch in pairs. Separate the pairs of fingers a little, so that we can see between them, and focus the eyes on the ground; that is, look at the ground between the fingers. We see what appear to be little sausages between the fingers; they occupy the positions between the ends of the fingers as seen by one eye, and the ends as seen by the other eye, as we can readily show by closing first one eye and then the other.

The Dominant Eye

Although normally we use two eyes, we do not use both to the same extent, and as a matter of fact many people can see much better out of one eye than out of the other. If we shut one eye and use the other only, it is always the stronger, or dominant, eye that we elect to use—just as a right-handed person will habitually use his right hand, and a left-handed person his left. Of course there may be some physical condition that compels the use of one eye in preference to the other; for example, the position of a microscope might make it more convenient to use a particular eye; but if there is no such limiting condition and we have a free choice, then it is the dominant eye that we elect to use.

There is a simple and interesting way in which you can decide which is your dominant eye. Roll up a loose cone of paper, about an inch across at the narrow end, and wide enough at the other end to be looked into with both eyes at once. Pick out an object in the room and look at it through the cone with both eyes at once. Now close each eye in turn. It will be found that the object is still visible to one eye, the dominant eye, but not to the other. The experiment has to be done not too slowly; when binocular vision gets properly to work, we begin to see that the cone seems to have two openings at the narrow end, each with its own small range of vision.

The Eyes as Range-finders

The difference in the appearance of an object as seen by the two eyes separately enables us to use our eyes as range-finders. The greater the difference between the two views, the nearer the object. Experience enables us to judge distances by observing the amount of difference, and the consequent increase or decrease in the apparent solidity of an object as we approach it or recede from it. In distant objects the difference fades out, and we have not this means of range-finding. In such extremely distant things as stars and planets the difference is indistinguishable from nothing, and we cannot judge by eye that a star is more distant than a planet, even though it may be a million times as far away.

One-eyed men are at a disadvantage in judging short distances because they lack the double vision that enables us to judge these distances with something like certainty. There is, however, another way in which the eyes judge distances, and this is open to one-eyed men as well as to those with two eyes. When we focus the eyes on an object the focus is different for near objects and for objects farther away; the strain of focusing is greater for near objects. The difference in focus, which we are aware of as a difference in strain, gives us a means of range-finding. This method is not so good as that based on double vision, and one-eyed men have to be careful about short distances, especially in the matter of knocking over tumblers of water.

Pictures that do not Coalesce

We have been observing that the two eyes see slightly different views of any object at which we look. The brain, assisted by a slight inward squint, joins the two pictures so that they coalesce, or run together, and give the effect of solidity. Very occasionally we see separate pictures with the two eyes, pictures which do not coalesce into a single one. On a sunny day we can make small rainbows by using a garden syringe. We turn our backs to the sun and spray water high into the air. We can see circles

of rainbow colours. We can see two small rainbows, overlapping, but a little distance apart from each other. We shut an eye, and only one bow is visible. By opening and shutting the eyes alternately and in rapid succession, we can see a rainbow apparently shift from side to side, always toward the eye that is open. The two pictures do not coalesce because they are not two views of the same thing, but pictures of two different rainbows, one circling round each eye. That is true of any rainbow; each eye sees its own bow. But an ordinary rainbow is so far off that the difference is not observable.

And Pictures that Do

Two lead pencils look very much alike, especially at the unsharpened ends, so that in looking at them we might have two views of the same object. We hold two pencils upright, about a foot from the eyes and three inches apart. We focus the eyes on a distant background. Four pictures of the pencils may be seen. We move the pencils inward till the two middle pictures come together, and concentrate our attention on the middle picture. Now we tilt the tops of the pencils a very short distance out to the sides, keeping the lower ends of the pencils at the same distance. When the eyes are adjusted, an enormous pencil may be seen, small at the front and increasing in width upwards and backwards. When the pencils are tilted out at the bottom the middle picture may be seen small at the top and increasing in size downwards and backwards. What we are actually seeing is parts of two pencils which the eyes make into a single picture. We get the effect of great size because the picture increases in size backwards, and not forwards as in ordinary perspective.

The Stereoscope

The photographic camera usually has one " eye " only. That is why it shows us things as if they were flat. Objects in photographs do not stand out solidly as the real objects do, so that photographs are disappointingly unreal. The stereoscope is an attempt at binocular vision, as it is

called; that is, vision with two eyes. The stereoscopic camera has two "eyes", set the same distance apart as the human eyes. It takes two photographs at the same time. One records what the left eye would see if looking at the scene alone; the other what the right eye would see. In the stereoscope the two photographs are placed side by side. We look at them through the two halves of a lens (Fig. 6). The lens is divided down the middle, and the two halves are interchanged, left to right and right to left. Looking through the lenses we see the photographs

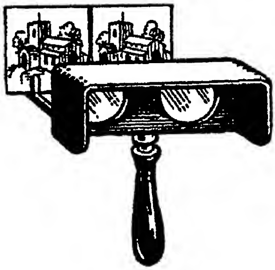


Fig. 6.

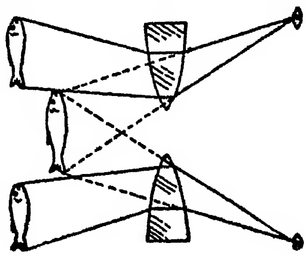


Fig. 7.

focused on the same spot. We thus get a single picture with a remarkable effect of solidity. Actually we see the foreground in one plane, and parts behind it in quite distinct planes. The separation is more distinct than it is in the real scene.

The two halves of the lens are interchanged (as in Fig. 7) to enable the eyes to see images of the two pictures in the same spot. Rays are bent toward the centre of the lens, and as we see back along the rays the lefthand picture is shifted a little to the right, and the righthand picture a little to the left.

We can, however, get a stereoscopic effect without using lenses; the unaided eyes can sometimes do the small amount of accommodation that is necessary, by means of a slight inward squint. The drawings in Fig. 8 show two views of objects as seen by the left eye and right eye respectively, at a distance of one foot. We have to separate the drawings so that each is seen by one eye only.

One way of doing this is to hold a sheet of cardboard upright between the drawings, and look down with one eye on each side of the partition; we have to see that the two drawings are equally illuminated. I find no difficulty in getting the stereoscopic effect without even the partition. I look down at the two drawings, and concentrate on the combined picture that forms between them. With a little adjustment I can get the effect I want. I have to turn the pictures a little askew to bring them to the same spot, and it may be necessary to move the eyes a little closer or farther away. But it is not difficult.

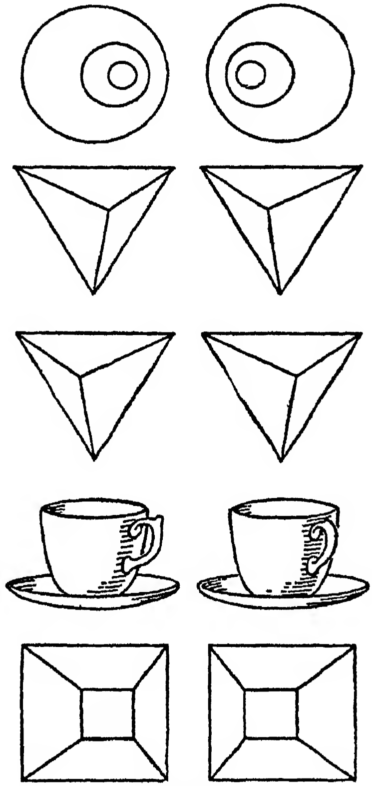


Fig. 8.

Stereoscopic Effect from One Picture

There is a very simple and effective way of getting a stereoscopic effect from an ordinary picture or photograph. Take a sheet of paper, say the size of an exercise book, and cut out a cross in the middle of it, the bars half an inch wide (Fig. 9). Lay a picture out flat on the table, and hold the sheet of paper upright, so that we can look down through the cross at the picture. The eyes are focused on the picture, not on the cross; that is, we look at the picture. When we look purposely for a stereoscopic effect we should get it easily enough. The explanation seems to be that the double vision of the cross, seen

out of focus, is referred to the flat picture, so that we imagine a stereoscopic effect and see details standing out boldly. Oddly enough, people who do not know what

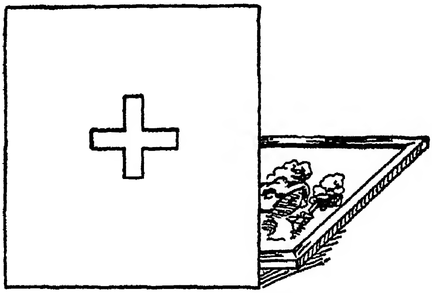


Fig. 9.

to look for often do not see anything unusual. It is an example of the well-known phenomenon that we see what we expect to see.

Stereoscopic Artists

The canvas on which an artist paints is flat, almost as flat as a photograph. But the artist is not content with flatness; he wants to represent the solid reality; he wants his pictures to have "depth", as we say. He aims at a stereoscopic effect. Now there are two kinds of solidity in a picture. There is the solidity of a solid body, and an artist imitates that by copying the light and shade of the actual object. The other kind of solidity is stereoscopic: the effect that makes nearer objects appear to stand out in front of those farther back. It is just this kind of solidity that the stereoscope gives us: the appearance of objects in different planes, one plane in front of another. Many modern artists outline solid objects in black or white so as to make them stand out from the background. Rembrandt sometimes outlined in red, but the red was subtly hidden so that it is not easily observed. Van Gogh went a step farther: in some of his pictures he used bold red lines to outline objects. Cézanne and other

modern artists have sometimes outlined in blue, and added patches of blue, in order to make objects stand out; they have used red and black in the same way. There is another device which is used by black-and-white artists particularly. On each side of a solid object there is a small part which is seen by one eye only. Artists carry over their lines into these parts so as to create the illusion of binocular vision. The top line of a hat, for example, is carried over a little at each side. Colours are carried over in the same way.

It is an interesting point that stereoscopic devices in painting tend to give us what the stereoscope gives: one plane in front of another. There is some sacrifice of the first kind of solidity in order to achieve the second.

Stereoscopic Films

Moving pictures are usually flat, like ordinary still pictures. Stereoscopic films have, however, been made. The problem is very much the same as that of the stereoscopic camera which takes still pictures. The camera has two "eyes", and it takes two sets of pictures simultaneously, one set right-eyed and the other left-eyed. The two films are printed separately; one set of pictures is tinted red and the other green. The two pictures are projected together on a screen, a little distance apart. The effect is very fuzzy because so far the eyes have no means of separating the two pictures. We want the right eye to see the red picture only, and the left eye the green. The separation is done by means of coloured spectacles. Each person in the theatre is provided with a pair, having a piece of green celluloid for the right eye-piece, and of red for the left. The right eye sees the red picture black, and the left eye sees the green picture black—which is what we want. The result is a remarkably stereoscopic picture.

No lens is necessary with films made in this way, because the two pictures are already close together. The eyes can without any noticeable strain do the very small amount of accommodation that is necessary to make the two coincide.

Anaglyphs

Books of pictures on the same principle as the stereoscopic film have been produced. They are meant to be looked at in the same way, through coloured celluloid. These pictures are called *anaglyphs*.

Many experiments have been carried out in attempts to produce screens that will give stereoscopic moving pictures without the use of lenses or coloured spectacles. Such a screen would have many vertical surfaces set at different angles, so as to reflect different parts of a composite picture to the two eyes separately. It is probable that truly stereoscopic films will be produced in this way, though it may be necessary to have specially constructed theatres.

What Parallax Is

Closely allied to binocular vision is the idea of parallax. If we hold a finger upright between the eyes a few inches from the face and shut the right eye, the finger appears over to the right; if we shut the left eye it appears over to the left. There is a very considerable shift in the apparent position of the finger. If we hold the finger a foot from the face there is still an apparent shift, but not nearly so much as before. We stand in a room and look out through a window. An upright bar on the window, or an upright edge, seems to shift in the same way against the background outside. We stand well back from the window and we find that the shift is considerably reduced.

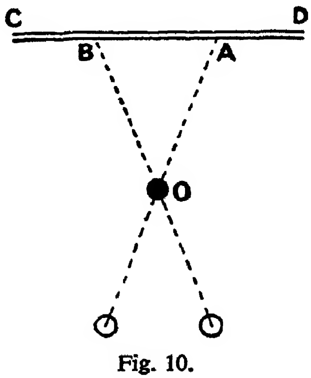


Fig. 10.

In Fig. 10 we have an object O seen against a background CD, say the wall of a room. The left eye sees the object in the direction OA, and the right in the direction OB.

The apparent change of position is called *parallax*. Parallax is the apparent shift of an object, *as seen against a*

background of some kind, when the observer changes his position.

Instead of opening and closing the eyes, we can increase the parallax by moving from one position to another. As we move to the right, we see that a near object, like the window bar, seems to move to the left compared with the background. Or, what is the same thing, the background seems to move with our eyes to the right, past nearer objects. On a railway journey, trees and houses and fields in the distance seem to be swinging round continually in the direction in which the train is moving.

Parallax on the Clock

We have to be careful about parallax when we look at the clock especially when the minute hand is near the hour or the half-hour. When we stand right in front of the clock we see the minute hand in its correct position, say over the half-hour mark. When we move to the right, the hand appears to move to the left, against the background of the clock face, and it shows perhaps a minute or more after the half-hour. When we walk over to the left, the hand appears to move to the right, and seems to show that it is not quite the half-hour.

The Parallax of Stars

As the earth spins round the sun we are changing our position rapidly. In six months we travel from one side of the orbit to the other, a distance, measured across the diameter, of 186 million miles. So there ought to be a shift in the apparent positions of the stars; nearer stars should have moved compared with very distant ones. Astronomers try to observe the parallax of nearer stars, using the very distant stars as a background. They judge these stars to be remote because of their dimness. Dimness is not an absolute test of remoteness, but there is a check on it: the stars used as a background should themselves show no observable parallax when compared with other apparently remote stars.

In Fig. 11, A and B are two positions of an observer at intervals of six months, so that AB represents the whole width of the earth's orbit, 186 million miles. C is a nearer star, and D is a very remote star which appears close to it in the sky. By comparison with D, the star C appears

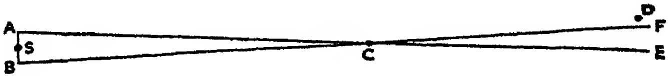


Fig. 11.

to move from E to F when the observer moves from A to B, in the opposite direction. The angle ACB is the parallax of the star C. (When parallaxes are given in tables, they are given as if one position of the observer were at the sun; so that the parallax in the table is half the angle ACB.)

Star parallaxes turn out to be extremely small, even with so great a movement of the observer. Parallaxes that have been measured are fractions of a second, and sometimes very small fractions. It is these parallaxes that are used in calculating the distances of stars.

Pinhole Images

A pinhole in a sheet of brown paper lets through a very small amount of light. On a bright day we make a pinhole in a sheet of paper, and we fix it over the window; there is no need to cover the window completely. That gives us what we want, a pin point of bright light.

We can use the light that comes through the pinhole to form a small image of the sun on a paper screen. We hold a sheet of white paper close up to the pinhole, and we get a very small and very bright image of the sun. We move the screen back. The circular image becomes bigger and bigger; and at the same time it becomes dimmer and dimmer, because the available light is spread out over a greater area. What we gain in area we lose in brightness.

A nail hole lets through more light than a pinhole, so it should give us a brighter image of the sun, though the

image may not be quite so sharp. I have been watching a sun image formed by light coming through a nail hole. I drew the paper screen back until the image was an inch across, and it was still quite bright. There were small clouds drifting across the sun, and they showed up faithfully on the sun's image. The clouds were going the wrong way: the real clouds were coming from the west, but the clouds that drifted over the sun's image appeared to be coming from the east.

Why a Pinhole produces an Image

It does seem odd that a pinhole should produce an image; the apparatus seems too simple for so remarkable a result. Fig. 12 helps to explain why light coming through a pinhole should produce an image. An arrow has been chosen as an illustration, because it is simple and distinctive in shape; but the arrow would have to be very brightly illuminated, because of the small amount of light that gets through the pinhole. A ray of light from the tip A of the arrow passes in a straight line through the pinhole P; it reaches the screen at D. At D we get a spot of light which is bright or dull, according as the tip of the arrow is bright or dull. Light from B passes through the pinhole, and we get a corresponding spot of light at E. Light from the part marked with a dot at C forms an image at F; and so on for every other point of the arrow. As a final result we get an inverted image of the arrow. And any other object or scene would of course give an inverted image on the screen, provided it were sufficiently lit up.

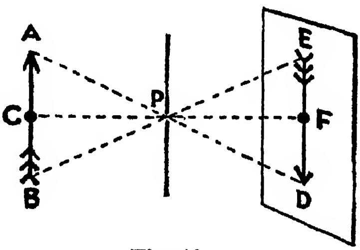


Fig. 12.

If we make a second pinhole in the opaque screen we get a second image of the arrow, and each additional pinhole gives an additional image. We can go on making more and more pinholes and obtaining more and more

images of the arrow. Finally, when the opaque screen is perforated everywhere, we get a mass of overlapping images that appear as a mere blur of light.

How to make a Pinhole Camera

We can do these experiments, and many others, much better if we have a little pinhole camera specially made for the purpose. It is very easy to make (Fig. 13). All we need is a small cardboard box, a small piece of opaque brown paper, and a square of grease-proof paper or tissue paper to cover the top of the box. We remove the lid

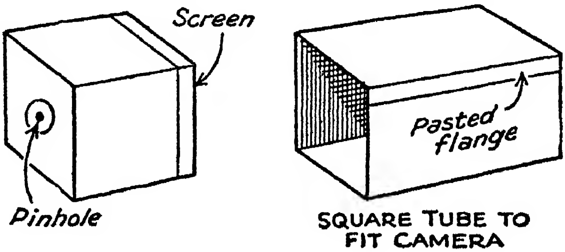


Fig. 13.

of the box. In the middle of the side opposite the lid we cut out a square or circle about 1½ inches across. We cover this hole with opaque brown paper pasted down. Over the open side, where the lid was, we paste a square of grease-proof paper or tissue paper, pasted down all round; this is to serve as a screen. We make a single pinhole in the middle of the brown paper, and the little camera is complete.

So little light comes through the pinhole that we need a very brightly lighted object to give a good image. The sun of course would give a bright but very tiny image on the screen. For most purposes it is better to use a lighted candle. If we hold the pinhole a few inches from a lighted candle we get a good inverted image of the candle flame and of the part of the candle just below it.

The image on the screen shows up brighter and clearer if the room is dark and lit only by the candle. Even

without darkening the room we can improve the apparent brightness of the image by cutting out light that falls on the screen from round about. We want to enclose the camera in a dark tube. We fold a sheet of dark-coloured paper so as to make a square or oblong tube just big enough for the camera to slide in, and paste the edges of the tube together. When the camera is being used we turn the screen away from the window or any other source of bright light.

Experiments with the Pinhole Camera

It is interesting to try the effect of moving the pinhole nearer to the candle and farther away. We begin by holding the camera so that the pinhole is halfway between the candle and the screen. The image is the same size as the candle-flame, and every flicker of the candle is

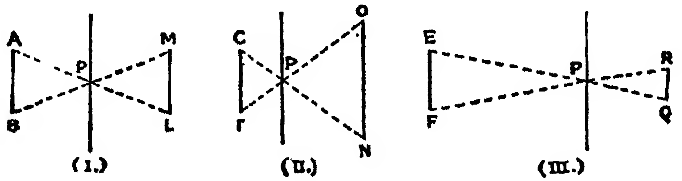


Fig. 14.

reproduced to size. Now we reduce the distance between candle and pinhole to a half. We get a greatly enlarged image; the image is indeed twice as big as the candle flame itself. Now we withdraw the candle till the distance from candle to pinhole is twice the distance from screen to pinhole. The image is reduced to half the size of the flame, and it goes on decreasing in size as the candle is still further withdrawn.

Fig. 14 shows why there should be these changes in the size of the image. At (i) P is the pinhole, AB is the height of an illuminated object (perhaps a candle flame), and LM is the height of the image formed on the screen by straight rays of light from AB. At (ii) the object has been moved up to half the distance, at CD. The image is

increased in height to NO. At (iii) the object is withdrawn to twice the distance, at EF, and the image is decreased to QR, which is half LM.

We have the same sort of thing happening in the eyes, though here there is a lens to form the image. As objects are withdrawn from the eyes, they form smaller and smaller images on the retina, and so they appear smaller and smaller to the observer. When we know the actual height of an object we can make an estimate of its distance by noting how high it appears to be. That is another way in which the eyes act as a range-finder. When we double the distance of an object we halve its apparent height; at three times the distance we get only a third, and so on.

Another interesting experiment we can do with the little pinhole camera is to enlarge the size of the hole so as to test the effect on the image. We can enlarge the hole by using wire nails of different thicknesses. We want a clear, clean hole in each case. A very small hole gives a sharp image. As the hole is increased in size the image becomes brighter, because more light gets through; but at the same time it becomes less sharp because images of the flame begin to overlap on the screen.

Pinhole Images under Trees

Pinhole images may be observed wherever bright light shines through small holes. One of the prettiest examples of the effect may be seen under trees when the sun shines brightly. The ground beneath a tree may be dappled with circles of light, some of them quite bright and others not nearly so bright. When we look up through the leaves toward the sun we may see the origin of the circles of light. We can see points of light where the sun shines through small gaps between the leaves. Each of these gaps acts in the same way as a pinhole: it lets through rays from the sun which produce an image of the sun on the ground below. Very small holes let through very little light and produce dull images; larger holes let through more light and produce brighter images.

We can imitate the dappled effect under trees very prettily by making holes of various sizes and shapes in a large sheet of paper, say a double sheet of newspaper. If we hold the sheet of paper in the sun close to the ground, we shall find that the sun shines through the holes and forms bright patches on the ground below. These bright patches have the same shapes as the holes through which the rays come. If we raise the sheet of paper the holes begin to lose their distinctive shapes, and to become round. When the sheet is raised still farther we have a number of round sun images on the ground.

If the distance is great enough for the size of the holes—it has to be greater for bigger holes—we get a sun image and not the shape of the hole. It is interesting to see the effect during a partial eclipse of the sun. The sun's disk is then partly covered by the moon and it does not appear to be completely round. The pinhole images, whether under trees or under a torn newspaper, faithfully reproduce its altered shape.

Sunspots in Pinhole Images

To see sunspots in a pinhole image we want a hole rather bigger than a pinhole, say the hole made by a thin nail, and as little light as possible should be allowed in the room other than what comes through the hole. This light should be made to fall on a white paper screen, which is moved backwards and forwards until it is in the correct position to show the sun's image. The image should be fairly big and fairly bright, but not too bright. The glare of the sun is so greatly reduced by the cutting out of all its light, save the small part that comes through the hole, that sunspots (if there are any at the moment) may be seen in the image.

I saw a remarkable example of this at Marylebone Station during the war. Blackout material on the glass roof cut out a large amount of light, but permitted pin-points of light to shine through. When the sun was not covered by clouds good sun images were formed on the platform, and sunspots could be seen on these images.

A Pinhole Camera for taking Photographs

A pinhole camera forms images of objects which are in front of it, and so it can be used for taking photographs. We need a much more carefully made camera than the one we have hitherto been using. It must exclude light, except what enters through the pinhole, and the pinhole must be very small in order to get a sharply defined picture. A cigar box does very well for the body of the camera. We begin by cutting a hole an inch or so square in the middle of one of the long sides. We want a piece of tin that will more than cover the hole; the kind of tin used for making airtight covers for cigarette and coffee tins will do. Cut out a piece big enough to cover the hole with half an inch to spare all round. Press the point of a large needle in the middle of the tin, so that it almost goes through but not quite; then rub away the projecting point with fine sandpaper, thus making a very small hole. We can finish the hole off with the point of a very fine needle. Fix the tin over the hole in the box with adhesive tape; and to make sure that no light can enter the camera except through the pinhole, cover the whole of the inside of the camera with dull black cloth, gummed on. As a final precaution we make a black cloth cover for the camera, and of course we must see that the pinhole is effectively covered until we want to make an exposure.

Fix a photographic plate or film along the side of the camera away from the pinhole, and it is then ready for use. So little light enters through the pinhole that a very long exposure is necessary, perhaps ten minutes or even more. The length of time depends on the particular camera, as well as on the brightness of the day; it can only be found by experience with your own camera.

A pinhole camera gives excellent results with buildings and similar still objects. It should give a good width of picture, and good definition. The exposure is so long that it is of course impossible to use the pinhole camera to photograph moving objects, but people or vehicles that happen to pass in front whilst a photograph is being taken leave so little trace on the plate or film that they do not

detract from the quality of the photograph. A friend of mine got an excellent picture of the National Gallery with a pinhole camera in spite of the large amount of traffic that passed in front of it.

Magnifying by Closeness

We hold a finger upright at arm's length, and close one eye; we see the finger clearly. We bring the finger closer to the open eye, and it appears to grow bigger and bigger. At a distance of about eight inches from the eye the finger still appears clear and distinct. When we bring it closer still it appears still bigger, but now it is blurred. The effect is even more striking if we use printed words instead of the finger. At about eight inches distance it is easy to read them, but when they are brought closer they become more and more blurred.

We can get an odd effect with a rather large pinhole in a sheet of paper by holding it close up to the eye. When we look at a light background we seem to see it through quite a large circular hole; the size of the hole is magnified by closeness. When we look at printed words held close up to the pinhole, we see them magnified, and we can read them when they are much closer than the usual range of distinct vision. The head of a pin held just behind the pinhole looks very big.

CHAPTER II

CANDLEPOWER AND THE FADING OF LIGHT

(Try to answer these questions first)

What is the " inverse square law "?
When we double our distance from a lamp how is the illumination affected?
How many times brighter is illumination on Mercury than on the earth?
Why is Mars a very uncomfortable planet?
Why does light fade according to the inverse square law?
What is meant by candlepower?
What is the standard candle?
What is a photometer?
How are shadows used to measure candlepower?
How is a grease-spot used to measure candle-power?
How is the photo-electric cell used to measure light?
What is meant by the magnitude of a star?
Why are some magnitudes minus?
How much brighter is a first magnitude star than a second magnitude star?
What is the magnitude of the sun?

We all know how rapidly the light of a lamp or a candle fades away as we move back from it. We see this effect most clearly with a lamp that is out in the open. Inside a room the walls and ceiling are lit up, and it is not quite

the same thing. Some of the light that falls on walls and ceiling and on furniture is reflected back, so that we get light from all sides as well as directly from the lamp. Out in the open there is little or nothing to reflect light; there may be a little reflection from the ground, but very little else. It is in these conditions that light fades away rapidly as we recede from it. Close up to the lamp there may be enough light to read by; we need not move back very far before we reach a point where reading is impossible. Even in a room where we get much light from walls and ceiling, we move up close to the lamp when we want a very bright light.

The Inverse Square

The rate at which the light of a lamp fades away has been measured in many different ways. It has been found that light fades away so rapidly that if we double our distance from a lamp we not merely halve the illumina-

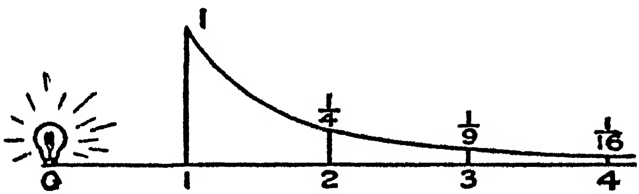


Fig. 15.

tion, but reduce it to a quarter (Fig. 15). If we hold a page of a book at a distance of five feet from a lamp, the page may be well enough illuminated to enable it to be read comfortably. At a distance of ten feet the illumination, that is, the brightness of the page, is reduced to a quarter and may not be strong enough for comfortable reading. At fifteen feet the illumination is reduced to a ninth, and at twenty feet to a sixteenth. At a distance

of 100 feet we have multiplied the distance by 20, and we find the illumination reduced to a mere $\frac{1}{20^2}$, or $\frac{1}{400}$ of what it is at five feet.

We say that the illumination is inversely proportional to the square of the distance from the lamp or other source of light. We can express that very neatly in algebra: at a distance x from a lamp the illumination is $\frac{1}{x^2}$ of what it is at unit distance.

That is the famous " inverse square law ".

The Disappointing Bonfire

It is not surprising to find that heat fades away in the same sort of way as light. It is not surprising, because heat is the same kind of thing as light. That is why the heating effect of a bonfire or a camp fire fades away with such disappointing rapidity. On an otherwise chilly night it may be intolerably hot close up to a roaring bonfire; but we do not have to move back many yards before it becomes cold. Indeed there is quite a narrow range within which an open-air fire gives a comfortable degree of heat, neither too hot nor too cold. It is very much the same when a fire is first lit in a cold room. Close up to the fire it is quite warm, but it rapidly becomes colder as we move away from it. There is a difference here between heat and light. The walls reflect light so that the room is at once flooded with light. But it takes some time for floor and walls and ceiling and furniture to become warm. When that has happened, however, heat is given out from all parts, and there is not the same difference in temperature between places near the fire and places further away from it. That is to say, we have the same sort of conditions as we have with reflected light. In a well warmed and ventilated room we can have pleasant warmth from the surroundings as well as from the fire, while the air in the room is cool and pleasant to breathe.

We often have to think of heat and light together because they are frequently radiated together by a glowing mass of stuff.

The glowing mass of the sun, the great central fire of the solar system, pours out light and heat in all directions. Nearly the whole of this prodigal output of heat and light passes off into space and is lost to the solar system. Only a very small fraction of it falls on the planets, and supplies them with heat and light. The earth, for example, gets just about a two-thousand-millionth of all the energy poured out by the sun—that is one part out of every two thousand million. We know this because at the distance of the earth the heat and light from the sun are spread out over the surface of a sphere with a radius of 93 million miles, and the earth fills about a two-thousand-millionth of this surface. Anyone who cares to can easily verify the calculation. The area of the sphere is: $4 \times 3\frac{1}{7} \times$ square of the radius (*i.e.*, the square of 93 million miles). The area to be allowed for on the earth is: $3\frac{1}{7} \times$ square of the radius (*i.e.*, the square of 4000 miles).

The Blaze of Mercury

Mercury is the planet nearest to the central fire which is also our lamp. We should therefore expect Mercury

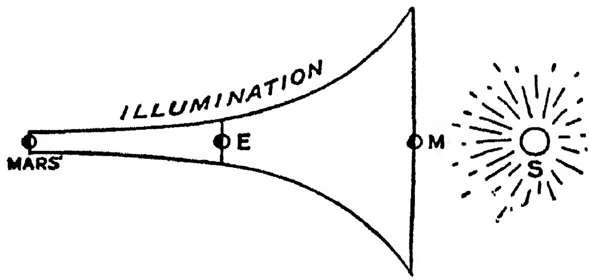


Fig. 16.

to be much more highly heated and much more brilliantly illuminated than the earth. The inverse square law

proves conclusively that this is so. The mean distance of Mercury from the sun is 36 million miles (Fig. 16). The earth, at a distance of 93 million miles, is $\frac{93}{36} = 2\frac{7}{12}$, or a little more than $2\frac{1}{2}$ times as far off from the sun as Mercury. We multiply $2\frac{1}{2}$ by itself, and find the square to be $6\frac{1}{4}$. We can now compare the lighting and heating effects of the sun on Mercury with its effects on the earth. The earth gets a little less than $\frac{1}{6\frac{1}{4}}$, which is less than a sixth, of the amounts of light and heat that are poured on Mercury by the sun. Another way of saying the same thing is this: a spot on the sunny side of Mercury gets more than six times as much light and heat as a similar spot on the earth. If we think of a hot summer day on the earth, and try to multiply the light and heat by six, we may begin to get some faint idea of the terrible glare of light, and the searing scorching heat on the side of Mercury that faces the too-near sun.

The Chill of Mars

We all have some interest in Mars, the planet that sometimes glows red and bright in the night sky, one of the few truly red stars. It is its nearness and likeness to the earth that interest us. Storytellers have filled Mars with people, some of them like men, and some not at all like men. They can give free rein to their fancies, and let them wander without restraint of fact. We know so little about the surface of Mars that there is no certain check on such fancies. We do not even know for certain whether the famous " canals " are real objects, or merely the result of eyestrain on the part of the observer. But we do know some things about conditions on Mars. We know that the Martian year is nearly twice as long as ours. We know too that the axis of Mars is tilted like that of the earth, so that Mars has seasons just as we have; and we can deduce that the Martian winter stretches on and on through eleven months. We know that Mars is 142 million miles from the sun. This is $\frac{142}{93}$, or a little

more than $1\frac{1}{2}$ times as far off as the earth. We multiply $1\frac{1}{2}$ by itself, and find that the square is $2\frac{1}{4}$. So illumination and heating effect on Mars are $\frac{1}{2\frac{1}{4}}$, or $\frac{4}{9}$ of what they are on the earth; and $\frac{4}{9}$ is a little less than half. Any spot on Mars gets a little less than half the heat and light that fall on a similar spot on the earth. We have to imagine our supplies of light and heat on cold winter days dimmed and chilled down to less than half. And we have to think of that doubly chilled winter stretching out intolerably over a period of eleven months. We begin to realise something about the chilly conditions on Mars, and to realise that these conditions would be a poor exchange for those of the comfortable earth.

Earth—the only Comfortable Planet

But Mars is a hothouse, glaringly lighted, compared with the outer planets: Jupiter, Saturn, Uranus, Neptune, Pluto. The major planets, beyond Mars, have only about a quarter of the density of the earth, so they cannot have cooled and settled down to the condition of the stable earth. But so far as light and heat from the sun are concerned, their conditions are miserable in the extreme. Neptune is one of the chilliest outposts of the solar system; it is more than 2790 million miles from the sun. That is, $\frac{2790}{93}$, or 30 times as far off as the earth. So illumination and heating effect are reduced to $\frac{1}{30^2}$, or $\frac{1}{900}$, of what they are on the earth. In the improbable event of there being inhabitants on Neptune, these unfortunates would have to live in a bitterly cold twilight during the mockery of a day, and to endure almost the chill of space in the night.

It was Tennyson who wrote:

Hesper, Venus, were we native to that splendour, or in Mars,
We should see the earth we groan in, fairest of their evening stars.

Could we dream of wars and carnage, lust and madness, craft and spite,
Roaring London, raving Paris, in that point of peaceful light?

Might we not in glancing heavenward on a star so silver fair,
Yearn, and clasp the hands, and murmur, "Would to God that I were there!"

Well, in spite of wars and carnage, and all else, I think we very justifiably might. The earth does at least offer the chance of a reasonable existence, which would not be possible on the other planets.

Why Light Fades

Let us look now at the question: Why should light and heat fade away in this rapid and uncomfortable fashion? The reason is not far to seek. We begin by thinking of light being radiated from a glowing body, and we can have this body so small that we can think of it as a mere point. Light and heat are being radiated in straight lines and in all directions. At a distance of one foot from the glowing centre the whole quantity of light and heat is spread out over the surface of a sphere with a radius of one foot (Fig. 17). At a distance of two feet from the centre it is spread over the surface of a sphere of radius two feet. Now to find an area we multiply two lengths; in the case of a sphere both lengths are the radius of the sphere. As both lengths are doubled the area is four times as great. (If anyone is doubtful: the area of a sphere is $4 \times 3\frac{1}{7} \times$ square of radius. So we have $4 \times 3\frac{1}{7} \times 1^2$ for the one-foot sphere, and $4 \times 3\frac{1}{7} \times 2^2$ for the two-foot sphere.) We have the same amounts of light and heat spread over a sphere four times as great, and so the illumination and heating effect are reduced to

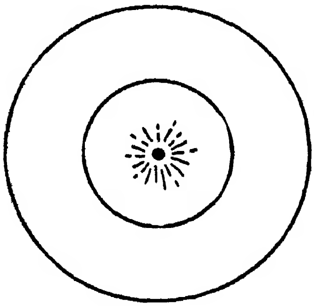


Fig. 17.

a quarter as great. We can readily extend the idea to a distance of 3 feet. The area is multiplied by $3 \times 3 = 9$, and so the illumination and heating effect are reduced to a ninth. We can go on to show that at a distance of 4 feet the illumination is one-sixteenth. Finally we arrive at the *inverse square law*: at a distance x from a glowing point, illumination and heating effects are $\frac{1}{x^2}$ of what they are at unit distance.

There is another way of looking at the inverse square law which some people find helpful. If we were to move up closer to a lamp we should see the lamp bigger. At half the distance we should see it twice as wide and twice as high, and therefore with four times the area; so that we should receive four times as much light from it. At a third of the distance we should receive nine times as much light; and so on. At the mean distance of Mercury the sun would appear $2\frac{1}{2}$ times as wide as when seen from the earth; so it would have $(2\frac{1}{2})^2 = 6\frac{1}{4}$ times the area, and would give $6\frac{1}{4}$ times as much heat and light as at the distance of the earth. As seen from Neptune the sun would have $\frac{1}{30}$ of its width as seen from the earth, and therefore $\frac{1}{900}$ of the area; and so it would give only $\frac{1}{900}$ as much light and heat.

Candlepower

When we want to measure anything at all we want a unit to measure it with—that is, a convenient standard amount of the thing to be measured. Before we buy an electric lamp we want to know how much light we can expect from it, so we enquire about its "candlepower." That is the unit we use for measuring the intensity of light given by a lamp. One candlepower is the intensity of light given by a standard candle. This standard candle is very carefully defined, as we should expect. It is made of spermaceti, a white waxy substance from the oil of the sperm whale; it is seven-eighths of an inch in diameter;

it burns at the rate of 120 grains per hour. At the time when this unit was fixed, that was the best that could be done to have an exact standard, though it was never very exact. We now have a less variable unit: the intensity of light given by five square millimetres of platinum when it is heated to the temperature at which it changes from solid to liquid. But whatever the method used to fix an exact standard, the unit still approximates to the old standard candle unit, and it is still called a candlepower.

A lamp of 100 candlepower gives the same intensity of light as 100 standard candles; it is as if we had a hundred of these candle flames, all equally bright and all concentrated in the single bright glow of the lamp. For ordinary purposes, when we are content with fair accuracy and do not seek a very exact measurement, we can use an ordinary wax candle as the standard. We want a candle of the kind sold six to the pound; we let the top part burn away, and we look for a steady even flame. That is our standard.

We sometimes want to know the candlepower of things we use to give light. We may want to know the candlepower of an electric lamp after it has been in use for some time and has lost part of its original brightness, or the candlepower of an electric torch, an oil lamp, a large candle, a taper, or even of a match, though the last is not easy to measure. The intensity of light that enters through a window can be measured; again this is not an easy measurement to make, and of course it varies greatly from time to time.

Measuring by Shadows

There are two simple ways of measuring candlepower that require no special apparatus, so that anyone can carry them out without much difficulty. Perhaps the simpler of the two methods is what is called a "shadow photometer." "Photometer" means "light measurer", and we make the measurement by comparing shadows. It is best to make the measurements at night. We fix up the simple apparatus, and then switch off the electric light while we make the measurement.

We want a small screen—a sheet of white paper will do—on which the shadows are to be cast (Fig. 18); we can fix it up against a pile of books. We also want a small upright rod. A pencil does very well; it may be fixed upright on a small square of cardboard by pressing a drawing-pin through from below. For a standard candle we can use a wax candle of the kind sold six to the pound; this is near enough to the standard for our purpose. We place the upright rod an inch or two from the screen, and put the candle a foot or so behind

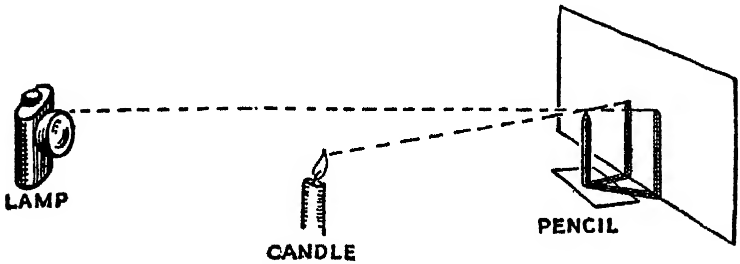


Fig. 18.

it, so that a shadow of the rod is cast on the screen. When we switch off the electric light we can see the amount of illumination given by a single candle. We can withdraw the candle, and notice how rapidly the screen becomes darker.

We place the lamp whose candlepower is to be measured so that it also casts a shadow of the rod on the screen. We want the two shadows side by side so that we may easily compare them. The candle shadow is not so dark as it was because it is now lit up by the lamp. Indeed each shadow is lit by one source of light only; the candle shadow by the lamp, and the lamp shadow by the candle. We move the lamp backwards or forwards till the two shadows are equally illuminated. If the lamp is very bright we may have to move the candle closer to the screen, so as to get a brighter illumination from it. When the necessary adjustments have been made the two sources

of light, candle and lamp, are giving equal illumination on the screen.

We now measure the distances of candle and lamp from the shadows on the screen. We know that the candlepower varies as the square of the distance from the illuminated screen. So we find:

$$\frac{\text{distance of lamp from shadow on screen}}{\text{distance of standard candle}}$$

We square this number, and that is the measured candlepower of the lamp. We should not expect the result to be extremely accurate. The chief source of error lies in the difficulty of ensuring that the two shadows are equally dense. However, if we are careful we can expect a reasonably accurate result, and certainly one that is near enough for most purposes.

The Grease-spot Light Measurer

The other simple method of measuring candlepower is by means of the "grease-spot photometer" (Fig. 19). As the first part of the name suggests, the apparatus is simple and homely. All we need is a small sheet of white paper

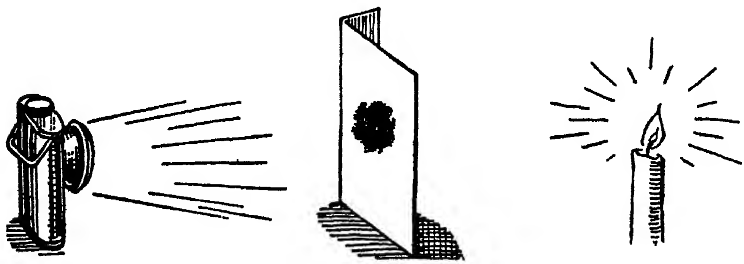


Fig. 19.

folded to enable it to stand upright. We use a small dab of lard or other fat to make a grease spot, an inch or so across, in the middle of the small paper screen. We may have to warm the screen slightly so as to get a good grease spot. We place the screen upright in the middle of the table with the lighted candle on one side of it. We

switch off the electric light. When we look at the screen from the side away from the candle, the grease spot shows up as a bright glow, because greasy paper is translucent, that is, it lets through light. We let the lamp we are testing throw its light on the side of the screen away from the candle. When the lamp is fairly close to the screen we may see the grease spot glow on the side towards the candle. The reason is that more light comes through from the lamp than from the candle. We have to adjust the position of the lamp so that the grease spot is barely visible, and looks the same from both sides. This is the difficult part of the experiment, and the chief source of error. Sometimes small mirrors are placed behind the screen, so that both sides of the grease spot may be seen at once, side by side. Even with this help it is not too easy to ensure that the two sides are equally illuminated. As before, we measure the distances of candle and lamp, this time from the grease spot. We find:

$$\frac{\text{distance of lamp from grease spot}}{\text{distance of standard candle}}$$

We square this number, and that is the candlepower of the lamp. It is interesting to find the candlepower of the same lamp by both methods and to compare the results.

The Photo-electric Cell

We now have much more accurate ways of measuring the intensity of light, and especially of measuring the feeble light given by a star, for example. The light from a single star may be allowed to fall on a photo-electric cell ("photo-electric" is "light-electric"), and the cell gives an electric current which is exactly proportional to the amount of light that falls on it. So, instead of the very difficult measurement of light, we can substitute the measurement of an electric current. There are exact ways of measuring electric currents, so we can have equally exact measurements of the intensity of light, and especially of the feeble light given by stars.

The Magnitude of Stars

We are all interested in the brightness of stars. We look up at a star and we say vaguely "That is a very bright star; it must be a star of the first magnitude. I wonder what it is called." Until recently that was just about all we could do about it; the only classification of stars was a vague classification by eye. The brightest of the stars were classified together as stars of the first magnitude even though they varied considerably amongst themselves in brightness. Stars that were a little less bright, like the Pole Star and most of the stars of the Plough

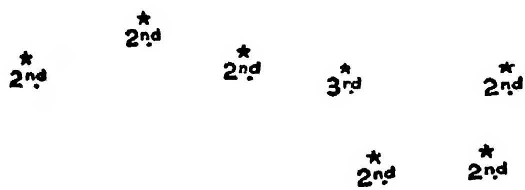


Fig. 20.

(Fig. 20), were classified together as stars of the second magnitude. Still less bright stars were called third magnitude stars; the rather dim star where the handle of the Plough joins on is a third magnitude star. Lower down the scale there were fourth and fifth magnitude stars; and finally the dimmest stars that can be seen with the naked eye were called sixth magnitude stars. But the whole system of classification was extremely vague.

The more exact measurements of brightness that are now possible show that each magnitude is about $2\frac{1}{2}$ times brighter than the next dimmer magnitude. The first magnitude is five magnitudes up on the sixth magnitude, so it should be $(2\frac{1}{2})^5$ times brighter.

$$\begin{aligned}(2\tfrac{1}{2})^5 &= 2\tfrac{1}{2} \times 2\tfrac{1}{2} \times 2\tfrac{1}{2} \times 2\tfrac{1}{2} \times 2\tfrac{1}{2} \\ &= \frac{3125}{32} \\ &= \text{not far short of } 100.\end{aligned}$$

This suggested a more exact scale in which a first magni-

tude star should be exactly a hundred times brighter than a sixth magnitude star. That is the scale which is now used. We need logarithms to find the exact difference between one magnitude and the next. The difference is $\sqrt[5]{100}$, and we find this to be 2·512, so that it is not greatly different from $2\frac{1}{2}$. A first magnitude star, in the new exact scale, is 2·512 times as bright as a second magnitude star. The vertical lines in Fig. 21 show the relative brightness of stars of the first six magnitudes.

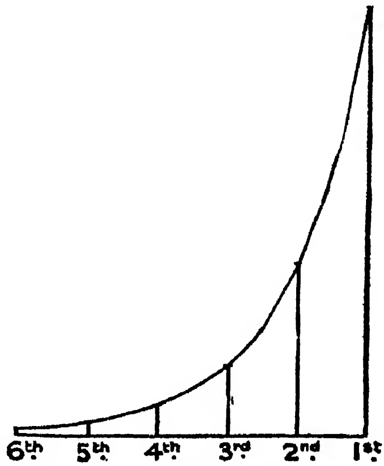


Fig. 21.

In the new scale stars are given fractional magnitudes. A magnitude of ·9 is a little brighter than first magnitude, and 1·1 is a little less bright than first magnitude. On the side of the Plough away from the handle there is a narrow triangle of rather dim stars; the narrow base points to two bright stars called Castor and Pollux; they are about as far apart as the Pointers of the Plough. Pollux has a magnitude of 1·21 and Castor of 1·58, so they differ in magnitude by ·37; Pollux is $2{\cdot}512^{\cdot 37}$, or 1·4 up on Castor; that is, it is $1\frac{2}{5}$ times as bright.

We have to remember that the smaller the magnitude the brighter is the star. We can go beyond magnitude 1. Magnitude 0 is 2·512 times as bright as magnitude 1, magnitude − 1 is 2·512 times as bright as magnitude 0, and so on. The brightest of all the stars is the planet Venus. When it is at its brightest it has a magnitude of − 4. That is five magnitudes up on magnitude 1 (0, − 1, − 2, − 3, − 4), so that Venus is a hundred times as bright as a standard first magnitude star.

The Sun's Magnitude

It is not easy to get a measure of the intense brightness of the sun. Nevertheless, the sun's magnitude has been measured; it is estimated at $-26{\cdot}7$, so that the sun is 27·7 magnitudes up on a first magnitude star. Another way of saying the same thing is that the sun is equivalent in brightness to:

$$2{\cdot}512^{27{\cdot}7} = 120{,}000{,}000{,}000$$

or 120 thousand million first magnitude stars. This is, of course, the brightness as it appears to us. Distant stars may be actually far brighter than the sun.

CHAPTER III

LIGHT WAVES

(Try to answer these questions first)

What is the modern explanation of light?
Why was the ether invented?
What is a quantum?
How are waves measured?
How long are light waves?
What are infra-red rays? How are they used?
Why is the setting sun red, and the sky blue?
What are ultra-violet rays?
How are X-rays produced?
Which rays come from radium?
What are Crooke's glass and Wood's glass?
How are wave-lengths and frequency connected?
How do light waves interfere?
What are Newton's rings?
What are interference colours? Where do we find them?
What is a diffraction grating?

We see that light usually travels in straight lines. We learn that it fades away according to the inverse square law. We can investigate the reflection and refraction of light. But what, after all, is light? We want an explanation that fits the facts—not some of the facts only, but all that we know about light.

Why the Ether was Invented

The modern explanation is that light consists of waves.

These waves are something like waves on the sea, though we must not push the analogy too far; they are *something* like waves on the sea. Now it seems that we cannot have waves unless there is something to wave. Sound waves, for example, are usually waves in the air; the air is the thing that waves. If we pump out air from a vessel we get no sound from it, even though a bell inside it may be doing all that a bell can do to create a sound. We get sound waves in water and in solids, as well as in the air, but there must be some material substance to carry them. The sun is probably full of riotous noises, noises that would crack the eardrums if we could hear them. But not the faintest sound reaches us from outer space because there is no material substance to carry such sound. Nor can we imagine sea waves without any sea. Lewis Carroll did indeed profess to imagine "a grin without a cat", but even the art of Sir John Tenniel had to leave some traces of the cat in order to express the grin.

It does seem as if there has to be some medium in which light waves can travel. It was to supply this medium that the ether was invented. We were told to imagine something with the most extraordinary properties, properties different from those of all material substances. It had to be perfectly elastic, and no known substance is perfectly elastic. Its density was supposed to be less than a trillionth of that of water. 40 tons of water would go into a tank 16 feet square and 5 feet deep; 40 tons of air would fill a large building; but 40 tons of ether would fill a space as big as the whole earth. The ether pervaded all space and ran through all matter. Perhaps the oddest property of all was that it offered no resistance to bodies moving through it; it did not seem even to have heard of friction.

Well, we were offered the hard alternative of accepting this extraordinary ether, or else of swallowing the idea of wave motion without anything to wave. Most people chose the ether as the less improbable of two apparently impossible ideas. The "luminiferous ether" was invented by Huygens, a famous Dutch physicist of the

seventeenth century; his idea has persisted until it is now accepted as a commonplace.

Nevertheless, the ether has struck a bad patch. Many scientists have given it up altogether, and substituted the idea that light is radiated energy with wave characteristics. We know the sort of mechanics that applies to the big, comparatively slow-moving things of everyday life; until recently scientists had the idea that the same kind of mechanics applied to small, fast-moving things. We had only to use a reducing glass, as it were, and we should have a picture of the mechanics of electrons, and light waves, and so on. That idea had to be scrapped because it did not work; and as soon as we scrap it we no longer need the always fantastic ether. Forget it. We can get our results by *picturing* light as waves, without assuming that there *are* such material waves. The mathematician says that light obeys wave equations, and goes on from there.

Quanta and Tadpoles

Another modern idea of light is that it consists of "quanta". We have to imagine, not continuous waves like waves on the sea, but minute atoms of light energy, each of the same magnitude as the others of its own kind. The evidence for this "atomic structure" of light is that when light is absorbed by atoms of matter, it is absorbed in definite small quantities: one quantum, two quanta, but never half a quantum or 1½ quanta.

My own feeling about quanta is that they are something like tadpoles: all wriggly, following one another in exact straight lines, and all the same size. All the same size, that is, for any particular kind of radiation; but a different kind of radiation would have tadpoles (or quanta) of a different size. Indeed the size of the quantum is proportional to the frequency of the light waves; blue light, for example, has a higher frequency and bigger quanta than red light. A whole tadpole (or quantum) can slip into an atom, or two, or even three; but there

are no half tadpoles. When atoms emit light, they give out whole tadpoles, but not fractions of tadpoles.

It is an interesting fact that the rays used in radiolocation are mechanically quantised. They are sent out in definite small pulses, and the instrument records the return of pulses reflected from aeroplanes.

Quanta are extremely minute quantities of energy. It takes something like a trillion quanta of visible light energy to make a foot-pound of work; that is, it would take the energy of a trillion quanta to raise a mass of a pound to a height of one foot. The retina is so extremely sensitive that a flash of a mere fifty quanta can be detected, and of this minute quantity of light only a tenth actually reaches the retina.

What Sea Waves Tell

Let us see what sea waves can tell us about light, for the two have points in common. We watch smoothly rolling waves on the sea, passing a boat. As each wave passes, the boat rises and then falls again; it is not carried forward by the wave. And that tells us that a sea wave is not a mass of water rushing forward; if it were it would carry the boat with it. It is the motion only that travels forward; as a wave passes the boat, each particle of water rises and then falls, but it does not move forward. There may be a little circular motion, but the chief movement is up and down. It amounts to this: as the wave passes there is a transference of energy along the direction of the wave.

We measure the length of a wave from crest to crest, or from trough to trough; the two distances are equal (Fig. 22). Sometimes we see smoothly rolling waves, and we can see that the waves are about equal in length. We have the same sort of measurement for light waves, that is, from crest to crest. And for light of the same colour the waves are exactly equal in length; that has been shown by careful measurement.

Let us watch small waves on a pond, where the surface

is usually smooth. We throw a stone into the middle of the pond, and we watch small waves move out in circles from the point where the stone hits the water. Waves

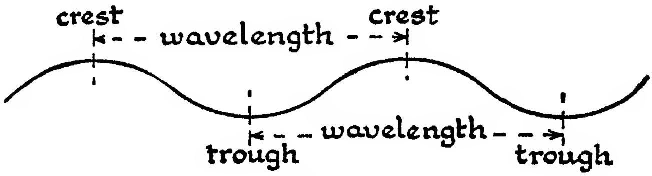


Fig. 22.

move out till they reach the side of the pond; then we see them reflected, or turned back, towards the middle. Light waves are not restricted to a level surface, like those on the pond. We imagine them moving out from a luminous point, like the surface of an expanding sphere; and we know they are reflected when they strike a suitable surface.

We throw two stones into a pond, and we see two sets of circular waves. We can see how they interfere with each other, as we say, whilst each wave retains its own circular form. Two crests coming together, for example, give an extra high crest at that spot; two troughs give an extra low trough; and a crest and a trough coming together simply cancel each other out. We can readily imagine that light waves in suitable conditions give interference effects.

Rope Waves

If we have any lingering doubts about the non-transference of material in waves, we can set them at rest by experimenting with a long rope. We lay the rope flat on the ground in a straight line, and we give one end of it a sharp up-and-down flick. We see a wave run along

the rope; each part of the rope rises and falls as the wave passes it. It is quite obvious that the material of the rope does not rush forward; the wave is a movement of energy from the hand which gives the up-and-down flick to the free end of the rope. If the far end is tied to a post we can have the wave reflected back from it. For this purpose the end of the rope should be nailed to the post; if there is a loose knot, most of the energy of the wave will expend itself on the knot.

We can start off two waves, one of them immediately after the other, and we can see them run along the rope at the same speed. These up-and-down waves are in a vertical plane. With a to-and-fro flick we can get a wave in a horizontal plane; and we can also make waves in oblique planes. We extend the idea to light waves. Ordinary light consists of light waves in many different planes, vertical, horizontal and oblique. It is only occasionally that we get light waves in one plane only; that is *polarised* light.

The Sequence of Light Waves

We can accept for the moment the ideas that wave-lengths are an important property of light waves, and that the wave-lengths can be measured. Wave-lengths are indeed amongst the most accurate of measurements.

It turns out that there is a continuous sequence of waves, varying in length from miles long down to a minute fraction of an inch; Fig. 23 contains a summary of them. The waves have many properties in common: they have the same speed; they exhibit the same kind of wave motion; they travel in straight lines; in suitable conditions they are reflected or refracted. Other properties depend on wave-lengths. One set of wave-lengths gives us waves that can be used as wireless signals and for radiolocation; shorter wave-lengths give heating effects; still shorter ones give the sensation of sight; and so on. There is no sudden break between one kind of wave and another. Heating effects, for example, gradually give

way to effects of vision as the wave-length shortens; then visible effects fade out as the wave-length becomes still

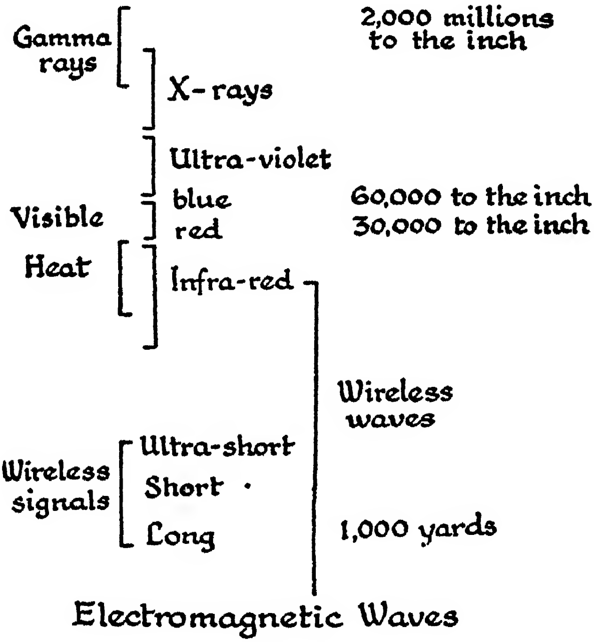


Fig. 23.

shorter. For these reasons we now class all these kinds of radiation together as light waves or electromagnetic waves. When we want to refer specifically to the waves that stimulate the sensation of vision we often call them visible rays, or even visible light.

Light has Weight

Newton had the idea that light consists of minute particles, which he called *corpuscles*, particles that are radiated in all directions by bodies sufficiently hot to

give light. If light did actually consist of such particles it should be attracted by any heavy body near which it happened to pass. If light were to pass the sun, for example, it should be drawn slightly out of its straight path by the heavy mass of the sun.

Einstein also put forward the theory that light is affected by gravity, and that rays of light are drawn out of their straight paths when they pass heavy bodies. That is, that light has weight. The effect is very small; it is too small to be observed when the rays pass a comparatively small body like the moon. We need a body like the sun, at whose surface gravity is 160 or 170 times as great as at the surface of the moon, to give an observable deviation. It is difficult to get observations because the glare of the sun swamps the dim light of stars seen

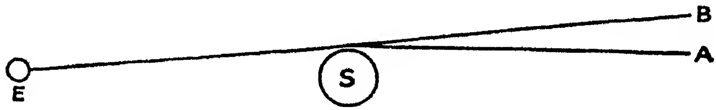


Fig. 24.

close to it. It is only when there is a total eclipse of the sun that the adjacent stars are visible. Photographs taken during a total eclipse show these stars. The photographs can be compared with others of the same stars taken at other times, and the comparison shows small shifts in the positions of stars near the sun.

Fig. 24 shows light from a star in the direction A, almost grazing the sun as it passes along towards the earth. The rays of light are drawn in towards the sun, and then proceed onward in straight lines. An observer on the earth sees the star back along the straight line ES; that is, he sees it in the direction B. Thus there is an outward shift from the sun in the apparent position of the star. The shift is greatly exaggerated in the diagram so as to make it visible; it takes good photographs to show that there is a shift at all.

The amount of shift depends on the apparent nearness of a star to the sun, that is, the closeness with which rays

of light from the star graze the sun. The effect of gravity fades out rapidly, according to the inverse square law, so that it is only near the sun that the effects can be observed. Measurements are not easy to make, but they have been made. The effect predicted by Einstein is double what it would be on Newton's assumptions. Measurements show that Einstein's theory is correct. The root difference between the two theories is this: Newton's corpuscles were material particles with the mass associated with material. Einstein introduced the revolutionary idea that light has mass *because it has energy*.

The Longer Waves

Let us look now at the sequence of electromagnetic waves.

The longest waves we know of are miles long. Next come the waves used as wireless signals; they vary in length from about a thousand yards down to a fraction of an inch. The next in length are the infra-red rays (" below the red "); the longest of these are an eightieth of an inch (80 to the inch), and the shortest 1/30,000 of an inch. The infra-red rays include the heat rays. They are longer than the visible rays, and for this reason they are not so easily turned aside.

The infra-red rays do not cause the sensation of sight, but they do affect a suitably sensitised photographic film. When certain dyes are used in the film we can actually take photographs by means of the shorter infra-red rays alone, and without the help of visible light; indeed a filter is used to cut out the visible rays. Infra-red photographs show clear details of scenes at a great distance, because the rays pass through fog and haze that would almost entirely scatter visible rays. Infra-red photographs have been taken of scenes as far away as three hundred miles.

Visible light is not necessary for these photographs, so it is possible to take them in the dark. They have been used to televise out of the dark. The scene is scanned with infra-red rays; the reflected rays fall on a photo-

electric cell and produce corresponding currents. These currents are used for broadcasting; they are transformed at the receiving end, and projected as a picture, just as if they had originated in visible light. Rays longer than infra-red rays are used for scanning the sky to detect the presence of aeroplanes. Their great penetration is valuable for this purpose.

Visible Light

The visible rays are shorter than the infra-red rays. The longest are the red rays which are a little less in length than the shortest infra-red rays. As the wave-length decreases we have the rainbow colours in order: red, orange, yellow, green, blue, violet. The shortest of the violet rays are a little less than half as long as the longest red rays. The difference in wave-length makes a considerable difference in penetrating power. During a fog street lamps look red because their red rays penetrate the fog, whereas blue rays are scattered. The setting sun looks red because red rays from the sun penetrate the slight haze of evening; the effect is increased by the fact that evening rays have penetrated a great depth of atmosphere before they reach us. The overhead sky often looks blue because the short blue waves are scattered by particles in the upper air, and thrown down to us.

Next in order of smallness after the visible rays come the ultra-violet rays (" beyond the violet "); these rays range down in length from 1/70,000 of an inch to 1/400,000 of an inch; there are 400,000 of the shortest ultra-violet rays to the inch. The ultra-violet rays have no visible effect, but they have considerable chemical effects, and they play a great part in photography. The mercury vapour lamp so much used in photography gives blue light and ultra-violet light.

X-rays

Still shorter than the ultra-violet rays are the famous X-rays, often called Röntgen rays after their discoverer. It takes something like 200 millions of these rays to

stretch an inch. They are produced by sending an electric discharge through a vacuum tube (Fig. 25). Streams of minute particles from the cathode (the negative electrode) are directed on to a metal target in the tube, and the target gives out X-rays.

X-rays have many valuable properties, including a photographic effect similar to that of visible and ultra-violet rays. Probably the most useful property they have is their power of penetrating solids that are opaque to

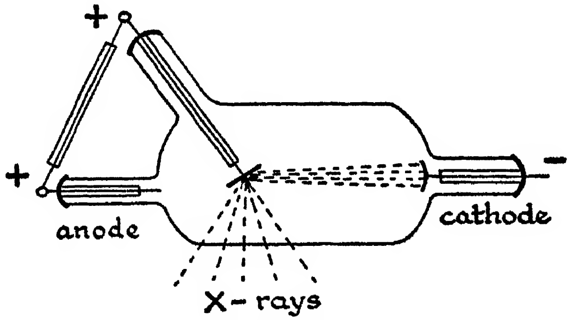


Fig. 25.

visible light rays. The flesh is transparent to X-rays, for example, so that we can have photographs taken which show the inside of the body. X-ray photographs are a great help in detecting the internal effects of disease and injury. They are a part of the ordinary technique in combating tuberculosis, and in finding whether bones have been fractured.

X-rays have been used in many investigations into the structure of matter. Moseley used them in making his great discovery of "atomic numbers". It was this discovery that finally and definitely arranged all the elements in an ordered sequence: hydrogen-1, helium-2, lithium-3, and so on, up to thorium-90, protoactinium-91, uranium-92. X-rays have also been used in many investigations into the structure of crystals. They have revealed how the molecules are arranged in crystals, an enquiry far beyond the limits of the most powerful microscope.

Rays from Radium

Gamma rays are similar to X-rays, but they come from a different source—the nuclei of atoms; they are given out by radium and other radio-active elements. These elements give out three kinds of rays which are called after the first three letters of the Greek alphabet: alpha, beta, and gamma (*a*, *b* and *g*). The alpha and beta rays turn out to be streams of minute, high-speed particles; the gamma rays are electromagnetic radiation like other light-waves. Gamma rays are used in treating cancer. They have a destructive effect on any material like flesh on which they fall. Their destructive effect is carefully directed against the cancer, and great care has to be exercised to ensure that healthy tissue is not injured. Radium is indeed dangerous stuff to deal with. It has to be stored in lead caskets sufficiently thick to prevent the rays getting through. On one occasion a tube containing radium was stolen in America. An urgent wireless appeal was sent out to the thieves. They were warned that if one of them happened to carry the tube in his waistcoat pocket he would have a terrible machine-gun bombarding his flesh through his clothing with minute particles travelling at the speed of 10,000 miles per second.

When rumour-mongers are hard put to it to find something new to have a rumour about they often fall back on the idea of a new ray. This usually has some deadly properties: it can wipe out brigades, divisions, whole armies, at a single sweep; it can depopulate and destroy cities. Unfortunately no one ever tells us anything definite about these new rays. If we knew the wave-length we might investigate them, but that is preserved as a deadly secret. We have glanced through the whole range of electromagnetic radiation, from the long wireless waves to the ultra-short gamma rays. There are not many parts of the range where a new ray might be hidden; nearly all of it has been investigated. I do not think anyone need be unduly perturbed by the idea of a deadly new ray that can kill from a distance. We have enough real dangers without inventing imaginary ones.

Transparency and Opacity

Many substances are transparent to one kind of radiation and opaque to other kinds. Perhaps the most spectacular example is the one already mentioned: flesh and other substances that are opaque to visible rays and transparent to X-rays. There are numerous other examples. Ordinary window glass is transparent to visible light and opaque to ultra-violet rays; so that plants in a greenhouse are usually shut off almost entirely from ultra-violet rays. Vitaglass is transparent to both visible and ultra-violet rays. Carpets might fade more quickly under light entering through vitaglass, because of the chemical effect of the ultra-violet rays; but on the other hand men and animals and plants might flourish.

Wood's glass is opaque to visible light, so that we cannot see through it. But it is transparent to ultra-violet rays.

Sun-glasses are intended to reduce glare, so they are made partly opaque to visible light. If they reduce glare only, there is a danger in wearing them. Bright light usually contains a superabundance of infra-red rays as well as visible rays, so that the eyes need protection. Normally we have two safeguards: the glare acts as a warning, and we turn the eyes away from it; and the pupils contract almost to pin-points, so as to exclude both kinds of rays. With sun-glasses both safeguards are missing. Sun-glasses reduce glare, so that we do not get the warning and do not turn away from it; and the pupils do not contract. An undue amount of infra-red rays can enter the eyes. This may have the effect of burning patches on the retina, and so impairing the vision. Good sun-glasses are not cheap; they are made of a kind of glass called Crooke's glass, which is partly opaque to infra-red rays as well as to visible light. They keep the balance between the two, and so prevent injury to the eyes.

Light Filters

Materials that are transparent to one kind of radiation and opaque to others are often referred to as filters.

We may have a filter which cuts out visible rays, and is transparent to infra-red rays; a filter of this kind is used in taking infra-red photographs. Coloured glasses are used as colour filters. Red glass is almost opaque to all visible rays except red; green glass is transparent to green light, and little else; and so on.

Colour filters make it possible to take coloured photographs. A red filter permits red light only to reach the photographic plate; and so we can have a photograph of all the red parts of a scene. With a green filter we can photograph the green parts, and with a blue filter the blue parts. We can print the red photograph red, the green one green, and the blue one blue; and so we can build up a composite photograph which gives a near approach to the colours of the original scene. The colouring is not perfect because no colour filter is perfect, and because the dyes are not likely to reproduce exactly the colours of the original scene. Coloured moving pictures suffer from the same defects.

Wave-length and Frequency

Instead of giving the wave-lengths of different kinds of radiation we sometimes give the *frequency*, that is, the number of waves that pass a given point in a second.

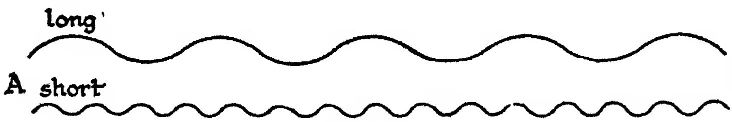


Fig. 26.

People are sometimes surprised that high frequency should always go with short wave-length, and low frequency with long waves. If we remember that all radiation travels at the same speed it is easy to see the reason: high frequency and short wave-length are two ways of saying the same thing.

The upper line in Fig. 26 represents long waves, and the lower line comparatively short waves. Suppose a

wave starting at A reaches B in a second, then all the waves between A and B must pass B in a second. The frequency of the long waves is 5 per second, and of the short waves 15 per second. The wave-lengths are $\frac{1}{5}$ of AB and $\frac{1}{15}$ of AB. When we multiply wave-length by frequency we get:

$$\tfrac{1}{5} \text{ of AB} \times 5 = \text{AB}$$

and

$$\tfrac{1}{15} \text{ of AB} \times 15 = \text{AB}$$

Wave-length × frequency = distance waves travel in a second.

The speed of electromagnetic waves is 186,300 miles per second, so we know that:

$$\text{wave-length} \times \text{frequency} = 186{,}300 \text{ miles.}$$

That is the relation between wave-length and frequency. With a wave-length of one mile the frequency is 186,300 per second. With a wave-length of $\frac{1}{10}$ mile the frequency is 1,863,000 per second. A wave-length of 1/10,000 inch has a frequency of: 186,300 × 5280 × 12 × 10,000 (that is the number of 10,000ths of an inch in 186,300 miles)

$$= 118{,}000{,}000{,}000{,}000 \text{ per second.}$$

That is a frequency of 118 billions per second, or 118×10^{12} per second.

Wireless frequencies are given in kilocycles, or kilocycles per second. A kilocycle is a frequency of 1000 per second, so that it is equivalent to a wave-length of 186·3 miles. Some of the wave-lengths of the B.B.C. are given as 342·1 m. 877 kc./s. 1500 m. 200 kc./s. 261·1 m. 1149 kc./s. ("kc./s." stands for kilocycles per second: 1149 kc./s. is a frequency of 1,149,000). In each case wave-length × frequency should equal the speed of light = 299,770 kilometres per second. So that 342·1 × 877, 1500 × 200, and 261·1 × 1149 should not differ greatly from 299,770. If there were a considerable difference then either the wave-length or the frequency must be given wrongly.

The Tides of Batsha

The tides of Batsha come into the story of light, because Newton and Young put them there. Newton used them as an illustration of one of his theories with regard to waves. Batsha is a port in Tongking. The tides reach it along two channels; one branch of the tide arrives about six hours after the other, with the result that Batsha is practically tideless, though places quite close to it have ample tides. We have the same kind of tidal interference at Southampton where the tides travel along two sides of the Isle of Wight.

The expression " tidal wave " is often misused to mean a wave originated by an earthquake. The true tidal wave is the world-wide wave that originates under the moon and sweeps up the shores of continents and into narrow seas to cause the tides. The period of the tidal wave is a little under twelve hours; that is the period between one high tide and the next high (the crests), or between one low tide and the next low tide (the troughs). At the port of Batsha there is a difference of half a wave-length (six hours) between successive crests or troughs, and so the waves cancel each other out: one tidal wave, for example, would produce high tide just when the wave from the other channel would produce low tide. On the other hand, if there were a difference of twelve hours, a whole wave-length, two crests would arrive together, and there would be a very high tide, followed by a very low tide when two troughs came together.

It was Young, the protagonist of the wave theory of light, who applied Newton's illustration to light-waves. If two light waves arrive, one of them half a wave-length behind the other, then the two waves cancel out, and there is darkness, so far as these particular waves are concerned. This is equally true if there is a difference of $1\frac{1}{2}$ or $2\frac{1}{2}$ wave-lengths, or any whole number plus a half. When the difference is an exact number of wave-lengths the waves reinforce one another and we get extra brightness.

How to get Interference Rings

The difficulty is of course to find a means of starting off one series of light waves exactly half a wave-length behind another series. We want two surfaces from which light can be reflected, and one of them at least should be transparent. If the two surfaces are sufficiently close together, then light from the lower surface may be half a wave-length behind light from the upper, transparent, surface. The lower surface may be a sheet of glass, which should be quite level. The upper surface may be a convex lens (Fig. 27). At one point the two surfaces touch.

Fig. 27.

A little way out from this point there is a ring along which the surfaces are half a wave-length apart. Farther out are rings along which the surfaces are 1, 1½, 2, 2½, 3, and so on, wave-lengths apart. The lens should have a great radius of curvature, that is to say, it should be almost flat, so that the rings may be an appreciable distance apart. If the radius of curvature is too small the rings are too close together to be seen separately.

We want light of a single wave-length (monochromatic, or single-colour light), and we can get this quite simply by dipping a piece of brick in strong soda solution and holding it in a blue gas flame. When this light falls on the lens we get a series of dark and bright rings. Near the centre is a dark ring. Light waves starting from the two surfaces—the upper surface of the glass sheet, and the surface of the lens close to it—are separated by half a wave-length; they cancel out and give a dark ring. Farther out, waves from the two surfaces are separated by a wave-length, and we get a bright ring. And so we get dark rings for ½, 1½, 2½, 3½, etc., wave-lengths, and alternating bright rings for 1, 2, 3, 4, etc., wave-lengths.

Measuring Light Waves

We can actually use this experiment to measure the wave-length of the light we are using. In the diagram (Fig. 28) BE is the curve of the lens, much exaggerated.

AB is the radius of curvature which we know, and which we call r; AE also equals r. BC is the distance of the first dark ring from the centre; so CE is half a wave-length, which we call x. We measure the distance BC; we will call this measurement m. DE is of course equal to BC; that is, DE $= m$. Also BD $=$ CE $= x$. We see at once that AD $= r - x$.

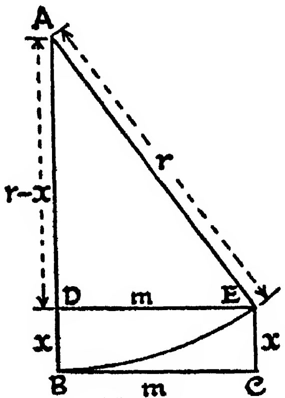


Fig. 28.

The triangle ADE has a right angle at D, so we can use Pythagoras' theorem:

$$AE^2 = AD^2 + DE^2$$

or

$$r^2 = (r - x)^2 + m^2$$
$$= r^2 - 2rx + x^2 + m^2$$

So $2rx = m^2 + x^2$

We know that x is very small (less than $\frac{1}{30,000}$ inch), so x^2 is extremely small $\left(\frac{1}{30,000^2} = \frac{1}{900,000,000}\right)$. It is so small that we can ignore it and say:

$$2rx = m^2$$

or

$$x = \frac{m^2}{2r}$$

Instead of measuring the radius of the first dark ring, we can measure a dark ring very much farther out. The radius of curvature may be 100 feet, and the radius of the 40th dark ring may be 1·559 inches. x would be $40\frac{1}{2}$ wave-lengths. So:

$$40\tfrac{1}{2} \text{ wave-lengths} = \frac{1{\cdot}559^2}{2r}$$
$$= \frac{1{\cdot}559^2}{2 \times 1200}$$
$$\text{wave-length} = \frac{1{\cdot}559^2}{40\frac{1}{2} \times 2 \times 1200}$$
$$= {\cdot}000025$$
$$= \frac{1}{40,000} \text{ inch.}$$

Interference Colours

We have been thinking of monochromatic light, that is light of a single wave-length. When ordinary light, with its mixture of many colours, falls on the lens, we get a different kind of interference effect. We know that the various colours have different wave-lengths, and so we find the various colours suppressed or reinforced at different distances from the centre. Instead of dark and bright rings we get rings of *interference colours*, sometimes called *Newton's rings*, because Newton was the first to investigate and explain these rings.

Whenever we get transparent materials separated by gaps which are down to the size of half a wave-length or $1\frac{1}{2}$ wave-lengths we are apt to get interference colours. A crack runs halfway through a piece of thick glass; along the crack we have two glass surfaces very close together, and very likely we get interference colours where the two surfaces all but touch.

We can get interference colours by pressing two pieces of glass close together. Both pieces must be clean and polished, for even a thin layer of dust is sufficient to keep them apart. When they are pressed tightly together interference colours should be seen.

A little oil falls on water. It is drawn out, by the greater surface tension of the water, into a sheet which becomes thinner and thinner. When the requisite thinness is attained, light reflected from the oil and water surfaces gives interference colours. Almost any street will show these colours on a wet day, because there is nearly always some oil on the ground.

The very thin wings of some flies show interference colours; these colours are indeed their chief beauty. The appearance of the wings is not unlike that of cracks in thick glass.

Soap Bubbles

A soap bubble is another thin transparent substance that shows interference colours; we get light reflected from both the inside and outside surfaces. If they are

carefully treated soap bubbles will last for some time. They have indeed been kept for as long as a year, but those were Methuselahs amongst bubbles. If we want them to last even for five minutes we must use a good soap solution. Filtered rain water or distilled water, soft soap, a little glycerine, and a single drop of ammonia—these should give a good solution. Toilet soap should not be used.

Everything we use in blowing bubbles should be dipped in the soap solution; otherwise the bubble will burst at once. We blow a bubble and let it rest on the open top of a tumbler or jar which has been damped with the soap solution; we blow the bubble till it overhangs slightly; then we leave it in a place free from draughts. At first the walls of the bubble may be so thick that we get nothing much in the way of colours. But the liquid drains away and the walls of the bubble become thinner. Then we get the interference colours, including a vivid orange red. Finally we may get a patch of black at the top—and then the bubble bursts.

Iridescent Clouds

One of the most beautiful examples of interference colours occurs in the sky, but only on rather rare occasions. The phenomenon is not, however, so rare as some people seem to think. I have seen it perhaps twenty times in a year, usually when my son, who keeps a pleased and watchful eye on the changing sky, draws my attention to it. On a level with the sun, and fifteen or twenty degrees away from it, we occasionally see a small luminous cloud, almost as bright as the sun itself. Less frequently we see along the inner edge of the cloud, that is on the side towards the sun, the interference colours, giving an exciting and beautiful opalescent effect. This effect is ascribed to sunlight falling on small ice crystals and so producing interference effects. I have just been watching one of these clouds a little above the level of the sun. For a quarter of an hour it was brilliantly painted with bright green and red.

Mother-of-Pearl

It is not only in transparent things that we find interference colours. We are apt to find them wherever there are surfaces close together from which light is reflected. Mother-of-pearl is composed of very thin layers of material, one over another. When it is polished across the ends of the layers we have the conditions we want—lines of material very close together—and we get the beautiful colouring we associate with mother-of-pearl.

If the colouring of mother-of-pearl is really due to the shape of the surface, then we should be able to get the same colours by imitating the surface, and this irrespective of the material we employ. The result has been achieved by pressing black wax on mother-of-pearl; the surface of the wax shows the interference colours.

The plumage of birds sometimes shows iridescent effects. The plumage has finely set lines, and these produce the conditions necessary for interference.

Diffraction Gratings

We can produce mechanically the conditions necessary for interference. Fine lines can be scored very close together on glass, with a diamond point. The lines stop the light, but light passes through the narrow gaps between. When the lines are sufficiently close we get the interference colours, both when light passes through the gaps, and when it is reflected from the lines.

Glass sheets ruled in this way are called *diffraction gratings*. As many as 40,000 lines to the inch have been ruled, but a quarter of that number gives satisfactory results. Such gratings are, of course, expensive. Cheaper gratings are made by pressing celluloid on the glass gratings so as to reproduce the lines. Diffraction gratings are commonly used for spreading out light into its constituent colours, especially when the colour lines are being used to detect the presence of various elements.

Wireless Interference

We can have interference with wireless waves just as much as with other electro-magnetic waves. Waves are sent out from the transmission station, and they may be received direct. But other waves may be reflected from the ionosphere, the electrified layer high up in the atmosphere. If it happens that the two sets of waves differ by about half a wave-length, then they cancel each other out almost completely, and we get very poor reception. At other times the ionosphere may begin at a different height, and there may be a difference of a whole wave-length; then the two waves reinforce each other, and reception is unusually good.

There are places where reception is invariably poor. They have the misfortune to receive waves with a difference of half a wave-length, and it appears that the ionosphere must remain fixed at an almost invariable level over those places.

If reception on one wave-length suffers badly from interference, the remedy is to try another.

CHAPTER IV

THE SPEED OF LIGHT

(Try to answer these questions first)

What is the speed of light?

How were the eclipses of Jupiter's moons used to find the speed of light?

How long does light take to cross the earth's orbit?

What is meant by "the aberration of light"?

How does rain illustrate aberration?

How is aberration used to find the speed of light?

Why does the direction of aberration change in periods of a year?

How was the speed of light measured across Paris?

Who measured it?

What is the shortest distance across which light has been timed?

How was a rotating mirror used to measure the speed of light?

How does the speed of light in water compare with the speed in air?

ONE of the things that bind the various kinds of radiation together, and make of them one family as it were, is that they all travel at the same speed. The speed is enormous, and unlike any other speed we know of; it is over 186,000 miles per second, and this is equal to $7\frac{1}{2}$ times round the world in a second. The speed is so great that usually it seems to us that light takes no time at all to travel from place to place. It is only across immense distances that the time taken by light can be observed without specially designed apparatus.

The speed of light has been timed in four quite different ways, and the results show a fair measure of agreement.

The Moons of Jupiter

The first measurement arose out of an oddity in the behaviour of Jupiter's moons. These moons are periodically eclipsed in the great umbra of the planet. They disappear quickly enough into the umbra for the time of an eclipse to be noted with fair accuracy. The eclipses follow one another in regular sequence, so that it is possible to predict their times. It was here that the odd

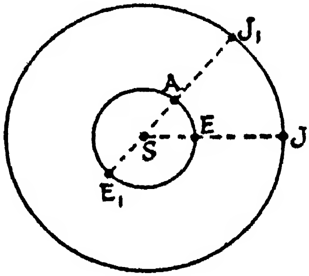


Fig. 29.

thing happened. The eclipses occurred a little later than the predicted times, then later still, until they were about a quarter of an hour late. But after that the eclipses began to occur nearer and nearer to the predicted times.

Now an astronomer differs from an astrologer in this: he expects his predictions to come true, and if they do not come true he wants to know why. Quite definitely there was something wrong with the predictions; something had been left out of the reasoning on which they were based. It was the Danish astronomer, Roemer, who found what it was. He ascribed the unpunctuality of the eclipses to the fact that light takes a certain time to travel from place to place.

Roemer's explanation is illustrated in Fig. 29. The two

circles are the orbits of the earth and Jupiter. When the two planets are at E and J, on the same side of the sun, they are as close together as possible. In order to reach the earth from Jupiter, light has to travel the distance JE.

When they are at E_1 and J_1 the earth and Jupiter are at opposite sides of the sun, and as far apart as possible. Light now has to travel the distance J_1E_1 in order to reach us. The extra distance is AE_1, and this is the whole width of the earth's orbit which we know to be 186 million miles.

It was found that the eclipses were $16\frac{1}{2}$ minutes late when the earth and Jupiter were at their greatest distance apart. Roemer's explanation was that light takes $16\frac{1}{2}$ minutes to travel 186 million miles. From this it is a simple matter to calculate the speed.

$$\begin{aligned}\text{Speed of light} &= \frac{\text{distance}}{\text{time}} = \frac{\text{186 million miles}}{16\frac{1}{2}\text{ minutes}} \\ &= \frac{186{,}000{,}000}{990}\text{ miles per second} \\ &= \text{nearly 188,000 miles per second.}\end{aligned}$$

That number is a little higher than those obtained by more exact methods.

Umbrellas and Telescopes

Roemer's measurement of the speed of light was made just before 1700. Thirty years later the English astronomer, Bradley, discovered the "aberration of light".

Aberration is a thing we are all familiar with. I saw a pretty example of it the other day, which anyone may observe on a rainy day. I was in a train, and the train was standing in a station. I saw the rain slanting down at forty-five degrees from the right (Fig. 30). The train moved off to the left, and very soon the rain appeared to be vertical. As we gathered speed, the rain appeared to slant down from the left. And then, unfortunately, we ran out of the station, and I saw the rain no more.

The rain apparently changes direction because we are

compounding with its velocity, the velocity of the train: we add a velocity equal and opposite to that of the train.

Another familiar example is often seen when we use

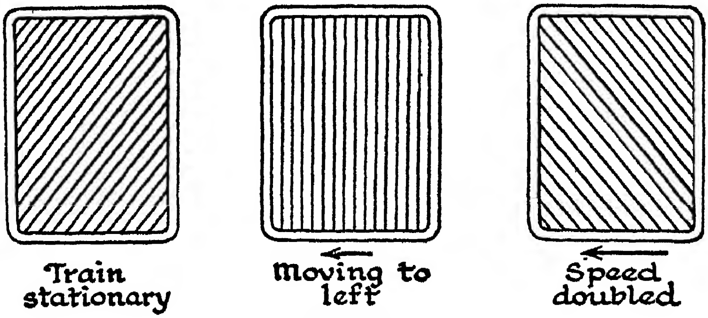


Fig. 30.

an umbrella to keep off the rain (Fig. 31). For simplicity we will imagine that the rain falls vertically. When we stand still we hold the umbrella upright. When we move

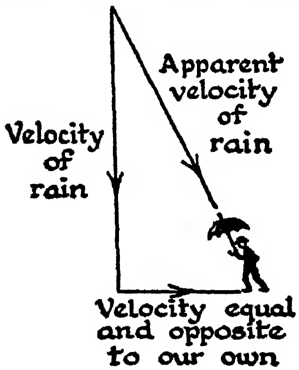


Fig. 31.

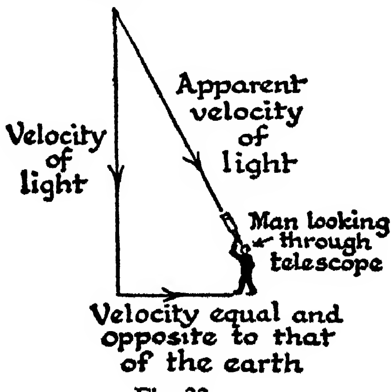


Fig. 32.

forward we find that we have to tilt the umbrella down, and the faster we move the more we have to tilt it. Again we have to add to the actual velocity of the rain a velocity equal and opposite to our own, in order to find the apparent velocity of the rain.

The angle between the real velocity of the rain and its apparent velocity is the aberration.

Now let us think of the parallel case of an astronomer looking at a star (Fig. 32). Instead of a downpour of rain there is light pouring down from the star. Instead of the forward walking motion, there is the motion of the earth in its orbit. Instead of the umbrella pointed up at the rain there is the telescope pointed at the star. The astronomer finds that he has to tilt the telescope down a little to receive the light of the star at the centre of the telescope. Six months later the earth is at the opposite point of its orbit, and moving in the opposite direction; the telescope has to be tilted the same amount as before, but in the opposite direction. The star in fact seems to describe a small ellipse round its actual position, an ellipse similar to the earth's orbit round the sun.

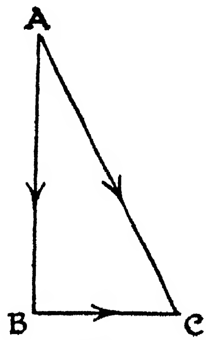


Fig. 33.

Bradley found that the tilt of the telescope, the aberration of light, is 20·43 seconds, not a great amount.

In Fig. 33 everything has been cleared from the diagram (Fig. 32) except the lines. AB is the actual velocity of light from an overhead star; AC is the apparent velocity; BC is a velocity equal and opposite to that of the earth in its orbit. The angle BAC is the aberration of light; it should be 20·43 seconds, but it would be impossible to show so small an angle in a diagram.

We want the speed of the earth in its orbit. The earth is 93 million miles from the sun, and its orbit is very nearly a circle, so its circumference is $2 \times 3{\cdot}14 \times 93$ million miles. It travels that distance in $365\frac{1}{4}$ days, so its speed is:

$$\frac{\text{distance}}{\text{time}} = \frac{2 \times 3{\cdot}14 \times 93 \text{ million}}{365\frac{1}{4}} \text{ miles per day}$$

$$= \frac{2 \times 3{\cdot}14 \times 93 \text{ million}}{365\frac{1}{4} \times 24 \times 60 \times 60} \text{ miles per second}$$

and that is just about $18\frac{1}{2}$ miles per second.

We know that $\frac{BC}{AB}$ is the tangent of angle A. We have to find this tangent, that is, the tangent of 20·43 seconds. For so small an angle the tangent is equal to the size of the angle in radians. We know too that 180° = 3·1416 radians, so that 1° = 3·1416 ÷ 180, and that is ·01745 radian. To find a second we divide by 60 × 60, or 3600. This gives: 1 second = ·000004848 radian. And 20·43 seconds is ·000099045 radian. So we know that the tangent of 20·43 seconds is ·000099045.

Now let us use this fact.

$$\tan 20{\cdot}43'' = \frac{BC}{AB} = \frac{\text{speed of earth}}{\text{speed of light}}$$

$$\text{So the speed of light} = \frac{\text{speed of earth}}{\tan 20{\cdot}43''}$$

$$= \frac{18\frac{1}{2}}{{\cdot}000099045} \text{ miles per second}$$

$$= 186{,}800 \text{ miles per second.}$$

Over the Rooftops

The two methods of measuring the speed of light which we have so far discussed were by-products as it were. The first was a by-product of an eclipse problem, and the second of Bradley's discovery of the aberration of light. Fizeau and Foucault on the other hand set out with the avowed intention of measuring the speed of light.

Fizeau proposed to time light across the rooftops of Paris. He set up a mirror nearly 5½ miles away from his station. He flashed a beam of light toward the mirror, and after some adjustment he got a return flash; the beam of light had travelled 10¾ miles, to and from the mirror.

He then fixed a toothed wheel in the path of the beam, so that the beam passed through the gap between two teeth; the return beam also passed through a similar gap. Then Fizeau rotated the wheel faster and faster. The return beam began to fade, and finally it faded out altogether. He noted the speed at which the wheel was

rotating. He doubled the speed of rotation, and once more the return beam became clearly visible.

Fizeau reasoned like this. The beam of light went out in small pulses, one pulse through each gap as it came in line with the beam. When the wheel rotated at the correct speed each of these pulses travelled to the distant mirror and back again just in time to be stopped by the next tooth; and so the return beam was stopped completely. When the speed of rotation was doubled each pulse of light returned through the next gap, and so the beam became visible again.

The toothed wheel had 720 teeth and 720 gaps of equal width between tooth and tooth. The return beam faded out when the wheel rotated at a speed of 12·6 revolutions per second. The number of gaps and teeth that flashed past the beam of light was, therefore, $2 \times 720 \times 12{\cdot}6$ per second, that is 18,144 per second, so that each took $\frac{1}{18{,}144}$ second to pass. And that is the time that light took to travel $10\frac{3}{4}$ miles, to and fro across the rooftops of Paris.

$$
\begin{aligned}
&10\tfrac{3}{4} \text{ miles in } \frac{1}{18{,}144} \text{ second}\\
&= 10\tfrac{3}{4} \times 18{,}144 \text{ miles per second}\\
&= \text{just over } 195{,}000 \text{ miles per second.}
\end{aligned}
$$

The result is rather too high, but then it is not easy to decide the exact moment at which light fades completely. Fizeau's measurement does at least show that previous measurements were not far wrong.

Foucault spins a Mirror

Foucault was the gyroscope man. He liked spinning things, so it is not surprising to find him spinning a mirror.

That is a thing that most boys have done. They hold a small mirror in bright sunlight, and by rotating it about an axis they send a small beam of light to and fro on walls and ceilings (Fig. 34). Foucault's mirror was rotated mechanically, so that he knew the exact number of rotations per second.

Near the rotating mirror he fixed up a small wire grid and a lens. A lamp behind the grid sent a beam of light to the mirror, and an image of the grid was formed in the mirror. Above the rotating mirror he fixed up a concave mirror. The shape of this mirror was part of a sphere with a radius of four yards; it was fixed at a distance of four yards from the rotating mirror. The concave mirror was placed so that a beam of light falling on the rotating mirror would be reflected to the concave mirror, and then back to the same spot on the rotating mirror. The return beam was reflected again from the rotating mirror, passed through the lens, and formed an image of the grid. Foucault adjusted his apparatus so that the image of the grid fell exactly on the grid itself (Fig. 35).

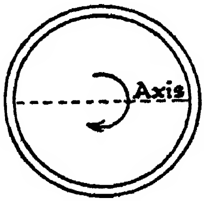


Fig. 34.

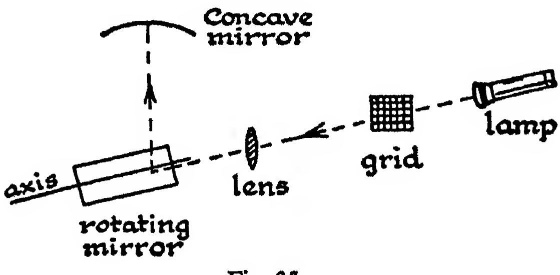


Fig. 35.

The beam of light travels eight yards to and fro between the two mirrors. While it is making this short journey the mirror has rotated slightly, and so the image of the grid is shifted away from the grid itself.

The mirror was made to rotate at the high speed of 800 revolutions per second. Image and grid were examined through a microscope, and the distance between them was measured. It was then a very simple calculation to find through what angle the mirror had turned. Foucault found the angle to be 25·3 seconds of arc.

The mirror was rotating 800 times per second, each revolution being a complete 360°. In a second the mirror turns:

$$\begin{aligned} 360 \times 800 \text{ degrees} &= 288{,}000 \text{ degrees} \\ &= 288{,}000 \times 3600 \text{ seconds of arc} \\ &= 1{,}036{,}800{,}000 \text{ seconds of arc.} \end{aligned}$$

So it rotates 25·3 seconds of arc in:

$$\begin{aligned} &\frac{25{\cdot}3}{1{,}036{,}800{,}000} \text{ second of time} \\ &= \frac{1}{40{,}980{,}000} \text{ of a second.} \end{aligned}$$

In that minute fraction of a second light travels 8 yards to and fro between the mirrors.

$$\begin{aligned} &8 \text{ yards in } \frac{1}{40{,}980{,}000} \text{ second} \\ &= 8 \times 40{,}980{,}000 \text{ yards per second} \\ &= \frac{8 \times 40{,}980{,}000}{1760} \text{ miles per second} \\ &= 186{,}300 \text{ miles per second.} \end{aligned}$$

The Best Method

Foucault's method of measuring the speed of light is by common consent easily the most accurate. When a scientific worker feels inspired to make a new determination of the speed of light he uses Foucault's method, though of course he tries to improve on the original apparatus. One improvement was to place the lens between the two mirrors. This enabled the concave mirror to be placed at a much greater distance from the rotating mirror without diminishing the brightness of the image. And this had the effect of increasing the distance through which light travelled, and therefore the angle through which the mirror rotated. The best recent measurements give the speed of light as 186,270 miles per second.

The method has been extended so as to find the speed

of light in water. A tube of water was placed between the two mirrors, so that light travelled through water in the distance over which it was timed. It turned out that light is slowed down in water, so that its speed is only three-quarters of its speed in air.

CHAPTER V

SEEING IN THE DARK

(Try to answer these questions first)

How does a poacher acquire "cat's eyes"?
Why does carrot eating not give good night vision?
What are the "rods and cones"?
What is the fovea?
What is the angle of distinct vision?
How long do the eyes take to become dark-adapted?
How can we keep them dark-adapted?
What precautions should be taken against glare?
How can one best see a dim object in the dark?
Which part of the eye sees movement best?
What precautions should a sentry take at night?
Why do trees look different at night?
How do night glasses help vision?
Why can the owl see well at night?
What is the "tunnel effect"?
Which colours are most visible in the dark?
How can we have our eyes dark-adapted without shutting out the light?

A POACHER goes out to poach. His illegal job has to be carried on in the dark; he dare not show a light. He has to find his way in the dark, visit his gins and traps in the dark, and spot his enemy, the gamekeeper, in the dark. On his side the gamekeeper has to work equally in the dark, because a light would give away his presence, besides hiding his enemy from him.

Sometimes we say that poacher and gamekeeper have " cat's eyes ", but that is only a figure of speech. Their eyes are no different from our own. It is the way they use them that is different.

The blackout taught us a lot about seeing in the dark. The things we learnt are still useful, especially when we are on dark country roads, so it is well not to forget them.

The Carrot Fallacy

We used to be told that carrots were the secret of night vision. If we ate lashings of carrots we should fill ourselves with vitamin A, and very soon we should be able to walk confidently in the dark. Obediently we ate carrots. We ate them raw and boiled, scraped and unscraped, whole and grated, alone and with other vegetables; we ate them as fruit. We talked carrots, and thought carrots; the whole nation was carrot conscious. And then we found we were just as blind as ever in the dark. There was a catch somewhere; we knew there would be.

It came into our heads that cats do not eat carrots, so it cannot be carrots that give them cat's eyes. And poachers and gamekeepers do not go about munching carrots all day long. There must be something else to it.

There is one little bit of truth in the carrot idea. Some people are short of vitamin A, and the eyes do need vitamin A. Carrots can help to supply the deficiency, and so to improve the condition of the eyes. They can help to bring the eyes up to normal. But normal eyes, however good, do not see in the dark unless we know how to use them.

The poacher learns by long experience and training how to use his eyes in the dark. The very necessities of his illegal occupation provide him with the best possible training. The airman, the tank-driver, the solitary sentinel, have to learn in a few weeks or months all the tricks of the trade of night-seeing. It is possible for them to learn quickly because we know quite a lot about how

the eyes see. To know why a thing is done is more than half the battle of learning how to do it.

Rods and Cones

We start with the retina, the sensitive screen at the back of the eyes. It is sensitive because it is crowded with nerve endings, each like the beginning of a telegraph wire to carry messages to the brain. There are two kinds

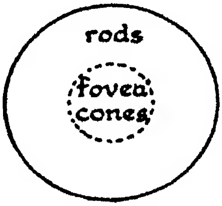


Fig. 36.

of these nerve endings: those of one kind are like rods, and those of the other kind like cones. The two kinds are not mixed evenly all over the retina. Most of the cones are in the middle of the screen, in a part of the retina called the *fovea*. Most of the rods are in the part of the retina outside the fovea (Fig. 36).

When light falls on the rods or cones, messages are sent off to the brain. And we see.

In a bright light, when we want to see a thing clearly, we look straight at it. Just now I am looking at a black-currant bush. I can see every currant clearly, with little bright spots where sunlight is reflected from them; I can see each separate leaf with its lights and shadows. Over to the left I am vaguely aware of a red-currant bush, but I can see no details. I shift my eyes a little to the left. The red-currants have come into my field of clear vision, and I can see each separate currant, as though the sun were shining into it. But the black-currants have faded out. I am vaguely aware of the bush, but it might be bare of currants for all I can see.

A few experiments of that kind will convince anyone

that in bright light we see clearly with the fovea only. The parts of the retina round the fovea give blurred images. In bright light we see by means of the cones.

Let us go out in the dark for some time and then come into a bright room. For a few moments our eyes are dazzled, and we are only conscious of a painful glare; we can see no details of the scene before us. It may be half a minute before we see really clearly; our eyes begin to move about, taking in details of one part of the scene after another. In that half minute our eyes have become fully light-adapted as we say. The cones have adapted themselves to the bright light.

Dark-adapted Eyes

When we return to the dark we are almost entirely blind. The cones do adapt themselves to the dark, but they do not respond to very faint light sufficiently to give us good night vision. For that we have to wait till the rods come into action. It is half an hour or more before the rods have fully recovered from the bright light.

The rods are far more sensitive to dim light than are the cones. They enable us to see by means of dim light that would have little effect on the cones. In bright light the rods are quickly put out of action, and they recover very slowly when the bright light is shut off.

That is the first thing we have to learn about seeing in the dark: it takes a long time to get the eyes fully adapted to the conditions. When a sentry is relieved, he should remain on duty until the eyes of the relief are fully dark-adapted.

The next lesson is this: having got our eyes dark-adapted, we have to take the greatest care not to have them put out of action again. A bright flash or glare can stun the rods in a fraction of a second, and we may have to wait some minutes for a full recovery.

We must avoid looking at lights. If we have to look towards a light we can at least shade the eyes with the hand. Gunners should close their eyes just as a gun is

fired so as to shut out the flash. The merest blink is all that is necessary, because the flash lasts only for a tenth of a second. To strike a match to light a cigarette is fatal to dark-adaptation.

When using a torch to find our way in the dark we have to make up our minds whether we mean to see with rods or cones. If we decide on the rods we put the torch away. If we decide on the cones we use a dim light all the time. The cones can adapt themselves to seeing in quite dim light, though not so dim as the light that brings the rods into full operation. The completely wrong method is to switch the torch on and off. When it is off we are almost completely blind. Even when it is switched on the eyes have to adapt themselves to the light, and this takes a few seconds each time it is done.

When we happened to be travelling by train in the black-out we got out of a lighted railway carriage and stepped on to an unlighted platform. That was a moment of danger because we were almost completely blind. We had to wait until our eyes began to adapt themselves to the dark before it was really safe to move. If we happened to be standing on the platform with eyes already dark-adapted, we might have seen people stumbling about, and we might have wondered why they were so stupid. The reason was of course that they were momentarily blind.

The same sort of thing happens when we leave a lighted house and go out into the dark. At first it seems to be pitch dark, because we cannot see. If we try to go forward we may perhaps stumble with nearly blind eyes into danger. It is better to stand still until the eyes begin to adapt themselves, and then go cautiously forward.

How to meet Glare

Let us stay out in the dark until our eyes are fully dark-adapted. We shut the left eye and keep it resolutely shut; we can best get the result by covering the eye with a hand. We walk into a lighted room. Very soon we can see clearly with the open eye. We remain in the light for perhaps two minutes. Then we go out into the dark

again. With the light-adapted right eye we can see very little at all, and nothing clearly. We close the right eye and open the left. There is an astonishing difference in the amount of detail we can see with the separate eyes. Closing the left eye has preserved its dark-adaptation. After five minutes in the dark there is still a noticeable difference in the amount of detail we can see with the two eyes.

Sometimes we find ourselves unavoidably in the glare of the headlights of a car. Unless we take proper precautions we shall find ourselves practically blind when the car has passed. We can avoid danger by shutting one eye before the light has time to affect it, and opening it when the car has passed. Then we can see clearly with the one dark-adapted eye.

If by any chance we have to look at a light we should always do so with one eye only.

Sometimes in the dark we get a glimpse of a faint star; we turn the eyes to look directly at it and it vanishes from sight. We get an impression that stars are elusive things, but the fault is not in our stars, but in ourselves. We have forgotten two things: in the dark we see with the rods; and the rods are not at the middle of the retina, but outside the fovea. To see clearly we want an image formed on the rods, so we do not look directly at the star but a little to one side of it.

Hold the arm straight out and bend the wrist, raising the palm vertically. Now if we want to see an object just to the left of the palm we fix the eyes on a point just to the right of it. We are looking about five degrees away from the object, and this enables an image to be formed on the rods. Of course we might just as well look five degrees to the left of the object, or above or below it. The point is that to see the object clearly we must look all round it, but not at it.

Most people know the star cluster called the Pleiades. It is up to the right over Orion, a constellation seen to the south in the winter months. Look directly at the Pleiades and try to count the number of stars in the cluster. They elude our efforts, especially the very elusive seventh star.

Now look at a point five degrees away from the cluster, and the counting becomes quite easy. (Five degrees, by the way, is the distance between the Pointers of the Plough.)

Out of the Tail of the Eye

An untrained sentry sees something move in the dark. He looks straight at it, and it vanishes from sight. He thinks his eyes have deceived him. And indeed they have, but not in the way he thinks. He probably saw something move "out of the tail of his eye"; but it disappeared when he looked straight at it, and it was then that his eyes deceived him. The outer parts of the retina, away from the fovea, are sensitive to movement. We best perceive movement in the dark when an image is formed on the outer part of the retina; we then see movement "out of the tail of the eye". A trained sentry looks all round a spot where he sees movement, but not at the spot itself. This method has the double advantage of forming images on the rods, and of giving an opportunity of perceiving movement with the part of the retina specially sensitive to movement.

The practice of looking to one side of an object instead of directly at it can be very useful to the driver of a car. Instead of looking straight ahead, he can see better by keeping his eyes on the hedge to the left. He would normally be watching a spot some distance in front, so that this method would give the correct angle for good night vision.

Resting the Eyes

Here is another easy experiment with the eyes. When they are fully dark-adapted, hold a finger at arm's length, upright against a starlit sky. Concentrate the eyes on the finger and hold it for a minute. That is quite a long time, and the result is surprising. The finger disappears from view.

The reason is that the rods tire much more easily than the cones. After a time they do not respond to the light that falls on them, and we do not see the finger. It is

inadvisable, therefore, to strain the eyes by staring into the dark. We should let them move slowly from point to point—slowly, because it is harder to see in the dark than in the light; and every couple of minutes we should close the eyes for ten seconds or so. The short rest keeps the rods from becoming tired, and the rested eyes remain capable of the best vision that is possible in the dim light of night.

When the Sun sets

Daylight fades and the darkness of night comes. The change from light to dark is more rapid than we are apt to think. Measurements show that the amount of light may decrease to a tenth in a space of twenty minutes. But we are not aware that the change is so rapid because our eyes adapt themselves gradually to the dimmer light as daylight fades. The pupils open to admit more light, and the cones of the retina adapt themselves to twilight conditions.

At first the landscape is coloured in the fading light; and then, almost suddenly, the colours vanish, and we are in a dim world of greys and blacks. That is the point at which the rods report for duty, and the cones begin to take their time off. Colour effects seem to originate in the cones. The rods are almost, if not entirely, colour-blind. Vision in the dark depends on contrasts of light and shade, and not at all on differences of colour.

There is of course a great difference in the degree of darkness between one night and another. The light of the full moon is just about the threshold, as we say, of colour vision; a little lighter and we should see colours. A starlit night without the moon has no more than the hundredth part of the light given by the full moon.

Sentries in the Dark

It is a moonlit night and we stand with our backs to the moon. We see a landscape lit everywhere evenly by white light. There is little contrast, and it is difficult to distinguish separate objects from the lighted background. We face the moon, and we see nearer objects clearly silhouetted

against a light background. When ships attack other ships at night they manœuvre so as to get the enemy between themselves and the moon (Fig. 37). The hulls of the enemy are then silhouetted against a light background, and clearly visible. In bright sunlight things are reversed. We try to get the enemy so that we can attack him out of the sun. He is clearly visible with the sun shining on him, whilst we ourselves are screened by the dazzle.

Two sentries are equally exposed in a moonlit landscape; one is facing the moon, the other has the moon behind him. The first sentry may be almost invisible to the second because he is equally illuminated with the background. But the second is clearly visible to the first because he is silhouetted against a light background.

Fig. 37.

The same sort of thing happens when a flare is dropped: it divides the landscape into two parts. Beyond the flare objects are equally lighted; there is little contrast, and little detail is visible. On the near side of the flare objects stand out in black shadow against a light background, and they are clearly visible. A sentry raises a hand to shield his eyes from the direct light of the flare, and he can then pick out anything between it and himself. But if the flare is behind him, he may be clearly visible to an enemy in front. It is obviously the time to take evasive action, and to merge himself, as well as he can, into the background.

Size and Visibility

Size has a lot to do with visibility, especially in the dark. I sometimes go down a road near where I live, on a very dark night. Even to dark-adapted eyes nothing much is visible in the street itself, because there is little contrast. But when I raise my eyes, the black masses of houses and trees are clearly visible against the slightly lighter sky. I steer my way by them.

A tall thin tree may be invisible in the dark, though the

upright corner of a house near it can be seen clearly. A tall post with the sign of an inn might not be there at all for all one can see of it; but the big mass of the inn cannot be mistaken; and yet both are looked at against the same background of sky, so that there is the same contrast.

In looking at a landscape under dim light we have to make allowance for the fact that small masses may be quite invisible, so that objects may present a different appearance at night from what they do in daylight. Trees, for example, sometimes look shorter at night

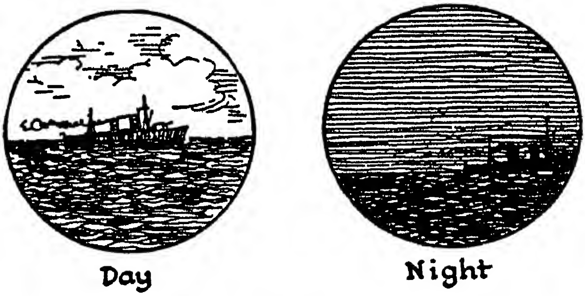


Fig. 38.

because long thin branches are invisible and only the sturdy trunk and bigger branches are seen.

There is another effect of the same kind which sometimes changes the appearance of objects at night. In dim light smaller objects seem to fade into the outlines of bigger ones which happen to be near them. What happens is that the lighter space between the large and small objects becomes invisible. A sentry standing beside a large tree or rock may be quite invisible from a distance, though he may be seen if he moves away from the large object that obscures him.

A Telescope in the Night

It may seem strange that objects invisible to the naked eyes should become visible when viewed through a telescope at night. The illumination of a distant object remains unchanged. Why then should a night glass

increase its visibility? In the first place the night glass feeds light into the whole of the pupil; and in the second place it magnifies distant objects. As we have seen, size alone is sufficient to make visible what would be invisible if the size were less.

When a seaman is using a telescope to observe a distant ship in the daytime he turns it so that the ship is in the middle of the field of view (Fig. 38); and so he has the image of the ship on the fovea, where the details can be best seen. But at night he turns the telescope so that the ship is as near the rim as possible; the image is thus formed on the rods where vision is most distinct at night.

Measuring Visibility

The fact that large objects are more easily seen than small objects giving the same degree of contrast helps us to get a measure of visibility in the night sky.

Take a piece of celluloid about two inches square, and with Indian ink draw concentric circles on it with radii increasing from $\frac{1}{8}$ inch up to 1 inch (Fig. 39). Try to make each circle a magnified version of the smaller ones. Thus the outline of the one-inch circle should be twice as thick as that of the half-inch circle.

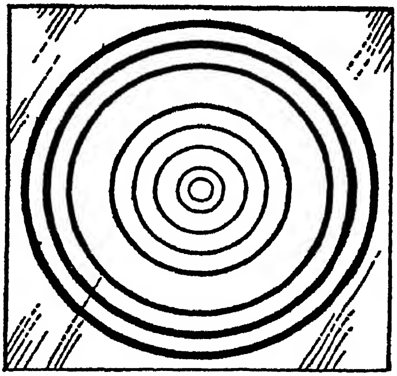


Fig. 39.

Hold the gauge at arm's length up against the night sky and see which is the smallest circle that is completely visible. The larger the circle the lower the visibility. We can use the gauge also to compare the brightness of different parts of the sky.

Different people get different results with the same gauge: what is comparatively light to one is quite dark to another. The difference lies of course in the eyes of

the observers. There are all sorts of variations in the retina. We know that there are various kinds of colour-blindness. Well, it appears that some people suffer from rod-blindness; their eyes have a much higher proportion of cones than usual, and a corresponding deficiency of rods. Such people might be described as night-blind. No amount of training would enable them to see well in the dark.

The Eyes of Night Birds

We know that some animals and birds have wonderful night vision, whereas others are almost blind at night. The difference used to be ascribed to the opening and closing of the pupils; we all know how widely the cat's pupils open at night, and how they shut down to the merest slits in bright light. But this explanation was never considered really satisfactory: the differences in the pupils were too small to account for the great differences in night vision. We now have a much more satisfactory explanation. In the retinas of owls and other night birds the nerve endings are entirely rods. They can therefore see well at night, but in daylight they can see nothing but a blur of light. Many day birds have retinas in which the nerve endings are all cones. They must have a wide range of clear vision during the day, and at night they must be almost blind. Man, as usual, is a compromise; he makes the second best of both worlds—the day world of the lark and the robin, and the night world of owls and prowling beasts.

The Tunnel Effect

In operations for cataract the natural lenses are removed from the eyes. Powerful lenses are worn as spectacles, which produce images on the fovea. The wearer sees very clearly in bright light, but he sees only the small region at which he looks directly. The lenses do not produce images on the rods, and so the usual blurred vision round the circle of clear vision is missing. There is a sort of "tunnel effect", as if one were looking down

a tube at a clearly defined scene with everything round it shut off. In the dark the man without natural lenses is almost completely blind. The cones have gone out of action, and no images are formed on the rods.

The same sort of tunnel effect is sometimes observed by airmen who fly at high altitudes. It may happen that the supply of oxygen is deficient, perhaps because the apparatus for supplying it is not functioning properly. One of the first effects is to put the rods out of action. Vision is restricted to the small central area, and the airman finds himself looking down a tunnel. That is a clear warning that there is something wrong with the oxygen supply.

Colours in the Dark

We can see a red light in the dark. No matter how dim it is, it always looks red—that is, so long as we can see it at all. It appears that red light affects the cones only and has no effect on the rods. When light is so subdued that the cones go out of action, then red light disappears entirely from sight. Red light may still reach the retina, but it is too faint to stir the cones to any response, and it does not affect the rods. So, if we want a lamp to be invisible at night beyond a short distance, we use one with a red light. Red is the colour for invisibility at night.

Blue light does affect the rods, so that blue is the best colour for visibility at night. When blue light is too dim to affect the cones, and so to give the sensation of blue, it may still be perceived as a glow by the rods.

Blue light has been tried for the lettering on buses and tramcars at night, but it is not satisfactory. It can be seen from a greater distance than red, but it is not easy to read. Red is the best colour to use under dark conditions. It is easy to read when it is near enough to affect the fovea, and it is soon hidden by distance.

It is well known to artists that blues and greens are accentuated in the half light, whereas reds are apt to lose their brilliance. Anyone may notice how brightly red flowers glow in the daytime, but in the dusk it is the green

leaves that glow; the red flowers look more nearly black.

Swaying Lights

Sometimes points of light appear to sway in the dark. We can reproduce this phenomenon with a torch in a dark room. We cover the light with a sufficient thickness of paper to exclude it completely. We make a small hole in the middle of the paper, a quarter of an inch across, and we fix red paper over it. We have to make sure that there is no other light visible except the one small circle of red. Even a pin-point of light from another source is enough to spoil the experiment. We start in the dark and look fixedly at the small red light. After a time it appears to sway to and fro, though we know very well it is not moving. If there is another object, however dim, to which we can relate the red light, the apparent movement ceases. If there is no such object, it is advisable not to carry the experiment too far. It should be another warning against staring in the dark.

Red Goggles

We have seen that red light affects the cones only, and not the rods. This gives us a method of getting the eyes dark-adapted without actually being in the dark. We wear red goggles for half an hour before going out into the dark. The goggles do not prevent us reading, but they enable the eyes to get dark-adapted by shutting out all light except that which does not affect the rods.

An officer on the bridge of a ship at night has a most trying task: he has to distinguish far-off lights in almost complete darkness. For a naval officer the task may be more trying still, for an enemy ship may approach without showing a light; all the sign he has of its presence is a slightly more solid blackness against the darkness of the night. A trained officer can detect a far-off ship long before untrained eyes are aware of it. But it is supremely necessary that he should preserve the dark adaptation of his eyes. If he has to consult a chart he does it under a red light, and he exposes his eyes even to this light for as short a time as possible.

CHAPTER VI

SHADOWS

(Try to answer these questions first)

What is an umbra? a penumbra?
How do we find the length of an umbra?
How would you place a halfpenny so as just to cover the sun?
How long is the earth's umbra?
When is there an eclipse of the moon?
In what direction does the earth's shadow move across the moon?
Why is a total eclipse of the sun only seen from a small part of the earth's surface?
What is an annular eclipse?
When do we see cloud shadows moving?
When do we see shadows without penumbras?
How can we throw a small shadow on the retina?
When do we get coloured shadows?

SHADOWS are exciting.

Or at least they can be. Ancient astronomers saw a shadow on the moon, and knew it for a picture of the earth; and the flat earth became to them a sphere. Coleridge's Ancient Mariner marvelled at the strange shadow of the becalmed ship. Artists have looked at shadows and seen in them things that other men missed. Scientists have created the most thrilling shadows.

On a bright sunny day we see the dark shadows of houses and trees and other objects. They seem black enough, especially by contrast with the surrounding glare,

and at first sight the edges seem straight and sharp. It is not till we begin to examine them carefully that we see how inaccurate our first impressions may be.

The Edges of Shadows

Look first at the shadow of a wall. Near the base, where the shadow begins, the edge of the shadow is straight and sharp enough, and there is a clear contrast between the dark shadow and the lighted ground beside

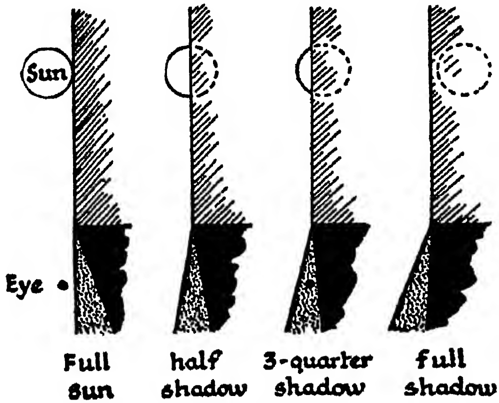


Fig. 40.

it which gets the full glare of sunlight. Farther out, the edge of the shadow gets more and more fuzzy, and the sharp contrast is lost.

The reason lies of course in the great sun itself. The sun is not a mere point of light, but a globe of considerable angular width. The width is 32 minutes, a little more than half a degree. When we look at the sun we want a piece of smoked glass to cut down the glare. We obtain it by holding a small piece of glass in the upper part of a candle flame where it is very smoky, and moving it to and fro till it has a good covering of soot.

Now let us take our stand behind the wall and look through the smoked glass at the sun. We stand so that the inner edge of the sun appears to touch the wall (Fig. 40). The eye is then just at the edge of the shadow. We move a little till only half the sun is visible. The eye then gets light from half the sun only; it is in half shadow. We move very slowly so that less and less of the sun is seen, and finally it is completely hidden. The eye is then in full shadow.

We can see the results of the gradual cutting off of the sun's light along the edges of any sun shadow. The shadow lightens gradually from the full shadow to the faint and indefinite outer edge. The dark central part of a shadow is called the *umbra*. The gradually lightening part round the umbra is called the *penumbra* (the " almost shadow ").

Umbra and Penumbra

We can find out a lot about the umbra from Fig. 41. S is the sun, and OP is an object in full sunlight. We draw lines from the upper and lower edges of the sun,

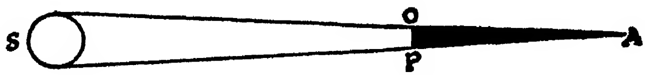


Fig. 41.

past the object. The shaded part OAP is the dark umbra. No light gets into this dark part directly from the sun. The angle OAP should really be half a degree, but it would be difficult to show such a small angle. It is necessary to exaggerate the angle in all these diagrams.

Fig. 41 tells only part of the story; Fig. 42 tells some more of it. We draw a straight line from C, the upper edge of the sun, past P, the lower edge of the object; this is the line CPE. DOF is a similar line from the lower edge of the sun. Nothing in the space FOPE gets the full light of the sun; everything in this space is shut off from at least part of its rays.

The umbra of a sun shadow does not extend indefinitely, because the sun is bigger than any of the objects of which it casts a shadow, and so the lines OA and PA close in. We have seen that on the earth they close in at an angle

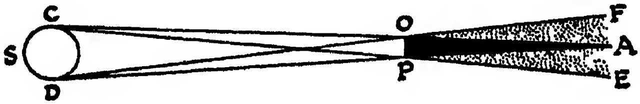


Fig. 42.

of about half a degree, and so we can tell how far the umbra of a sun shadow extends. We might, with extreme care, drawn an angle of half a degree; we can get the result much more easily by calculation. We need a little trigonometry, but fortunately it is very easy trigonometry.

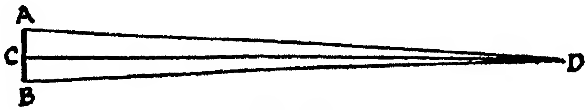


Fig. 43.

In Fig. 43 AB is an object, and ADB is the umbra cast by the sun; so angle ADB is about 32 minutes. DC is the perpendicular from D to AB. So angle ADC = half angle ADB = 16 minutes. Now the fraction, or ratio, $\frac{AD}{AC}$ is called the cosecant of angle ADC (we write "cosec" for short). So:

$$\frac{AD}{AC} = \text{cosec ADC} = \text{cosec } 16'.$$

We look up the cosecant of 16 minutes in a book of trigonometrical tables, and we find that it is 214·9

$$\frac{AD}{AC} = 214{\cdot}9.$$

That is to say, AD, which is the length of the umbra, is about 215 times as long as AC, which is half the width

of the object. To find the length of the umbra of an object cast by the sun on or near the earth, we have only to multiply half the width of the object by 214·9, or the width of the object by 108. 108 is a convenient approximation because 108 inches is three yards.

We have to take the least width of the object, because the umbra comes to an end more quickly in this direction than in the direction of a greater width. And this is of course the length of the umbra when there is nothing to interfere with it. The umbra may end much sooner when it falls on the ground or on a wall.

The Shadow of a Halfpenny

A halfpenny is an inch across, so the umbra of a halfpenny cast by the sun has a length of about 108 inches, or about 3 yards. In order to see this umbra we should have to hold the coin straight across the line from our eyes to the sun.

It is more convenient to use a circle of cardboard or

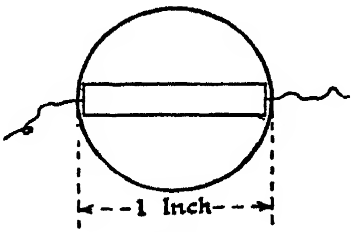


Fig. 44.

thick brown paper instead of a halfpenny. We cut out a circle an inch across, and we fix a long thread across it with paste and a strip of paper (Fig. 44). We use the thread and two drawing pins to fix the circle on the frame of a window through which the sun is shining. We turn the circle so that it is in the direction we want, that is, across the face of the sun.

Now let us use a sheet of white paper as a screen. We

hold the screen just behind the circle, and if the sun is bright we get a dark, clear, almost sharp, circular shadow. We withdraw the screen slowly, keeping it parallel to the circle. The umbra dwindles in size, still keeping its circular shape, and the fuzzy penumbra slowly gets wider. At a distance of about three yards the umbra vanishes altogether, and we are left with a vague fuzziness a couple of inches wide. This is the penumbra. If we close one eye, and stand with the other eye at the point where the umbra vanishes, that is, about three yards from the circle, we can see the circle exactly cover the sun.

If we use a small ball instead of the circle there is no need to adjust it across the sun. The umbra is always a cone, however the ball is held.

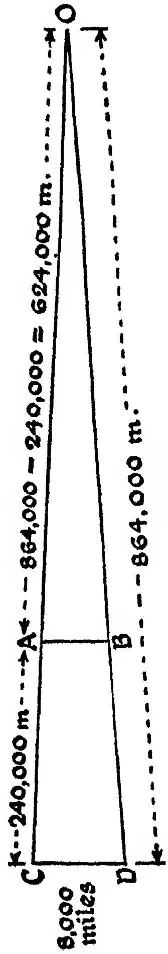


Fig. 45.

The Earth's Umbra

The cone of the earth's umbra is a really big thing. We can readily find how long it is. The diameter of the earth is nearly 8000 miles, so the length of the umbra is:

$$8000 \times 108 = 864{,}000 \text{ miles.}$$

A dweller on a satellite 860,000, or so, miles from the earth, if there were indeed such a dweller on such a satellite, might see the earth totally eclipse the sun when his satellite happened to pass the point where the umbra ends. Beyond 864,000 miles there would be no possibility of a total eclipse of the sun by the earth.

A Man in the Moon, the real moon, would have a much better chance of seeing the earth eclipse the sun

completely, because the earth's umbra has a considerable width at the distance of the moon. Fig. 45 shows the measurements we need to know in order to find this width. We have the diameter of the earth—8000 miles, the length of the earth's umbra—864,000 miles, the distance of the moon—240,000 miles. We have the two similar triangles, OAB and OCD. The sides of the triangles are in proportion, so:

$$\frac{AB}{CD} = \frac{OA}{OC}$$

or

$$\frac{AB}{8000} = \frac{624{,}000}{864{,}000}$$

We readily find that AB = 5800 miles. There is ample room in this wide umbra for the 2160 miles of the moon's diameter. The moon is not always obliging enough to enter the earth's shadow. At full moon it usually misses the shadow by being too high in the sky, or too low.

When the moon is completely in the earth's umbra the highly improbable lunarite sees a total eclipse of the sun by the earth. We ourselves see a total eclipse of the moon. We see the moon move into the penumbra, moving from right to left, so that the shadow appears to creep across the moon's face from left to right. The penumbra darkens and reddens the moon. Then we see the moon move into the dense black umbra, until, if it is a total eclipse, the moon is completely hidden from the light of the sun. Then the moon emerges into the penumbra, and finally it is completely clear of the earth's shadow, and shines once more as a brilliant full moon.

It was noted long ago that when the moon moves into the earth's umbra, the edge of the umbra on the moon is always part of a circle. That is one of many reasons for believing that the earth is approximately spherical in shape.

The Moon's Umbra

The moon does not carry nearly so long an umbra as the earth because of its much smaller size. The diameter of the moon is 2160 miles, so the length of its umbra is:

$$2160 \times 108 = 233{,}280 \text{ miles.}$$

The distance of the moon from the earth varies between about 220,000 and 250,000 miles; consequently at new moon, when the moon is between earth and sun, the end of the moon's umbra either just reaches the earth with a little to spare, or falls just short of it (Fig. 46). That is why a total eclipse of the sun can be seen from a very small part only of the earth's surface. Those who are fortunate enough to be in the path of the umbra may see the moon cross the sun from right to left. As the moon crosses, the penumbra becomes darker, until the last part of the sun's disc is covered. There is a sudden darkness as the last of the sun's light is shut off, and the corona, the flames that surround the sun and are usually swamped by its glare, suddenly becomes visible. Then the rim of the sun appears on the right, and the moon slowly moves off to the left.

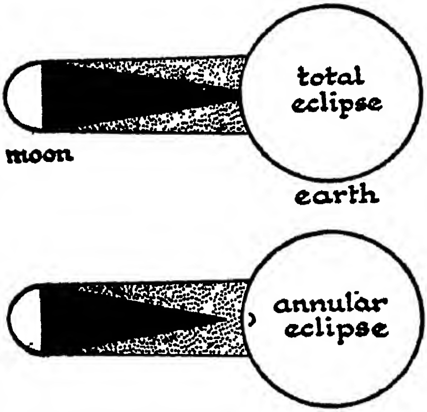


Fig. 46.

When the apex of the moon's umbra falls just short of the earth, the most that can be seen is an "annular (ring-shaped) eclipse". At the height of such an eclipse the dark circle of the moon can be seen with a bright circle of uncovered sun round it.

Width of a Penumbra

It is somehow disappointing to find that even in the brightest sunshine the roofs of houses do not give sharply defined shadows; there is always the fuzzy edge of the penumbra. We can find the width of the penumbra in a way similar to that in which we found the length of the umbra.

In Fig. 47 the angle CED should be half a degree, and so also should be the angle ECF. It is the angle ECF, between the edges of umbra and penumbra, that we want.

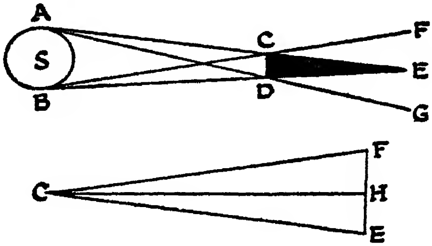


Fig. 47.

We separate it from the rest of the diagram, and we draw the perpendicular CH to FE.

Just as before we have:

$$\text{cosec FCH} = \text{cosec } 16' = \text{about } 216 = \frac{\text{CF}}{\text{FH}}.$$

So $\text{FH} = \frac{\text{CF}}{216}$, or $\text{FE} = \frac{\text{CF}}{108}$. To find the width of the penumbra at a distance CF from the object we divide this distance by 108. This gives the width straight across the penumbra. When the penumbra is cast on a pavement its width is exaggerated—slightly when the sun is high in the sky, and much more when the sun is low. Fig. 48 shows how this comes about. When the sun is

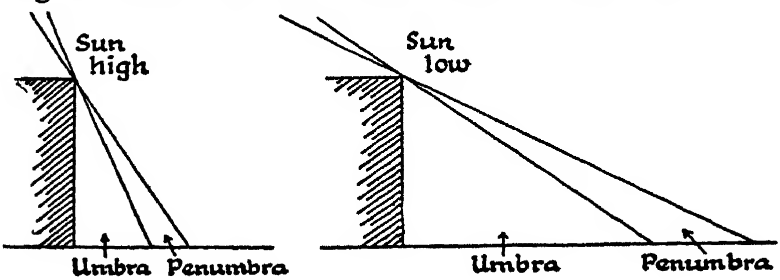


Fig. 48.

overhead at noon in the tropics there is no umbra, and the penumbra is reduced to its narrowest possible width.

The Penumbras of New York and the Moon

Here is a building 100 feet high (Fig. 49). A bright sun throws a shadow dark by contrast, and on a wide pavement below there is the edge of the roof-shadow with its fuzzy penumbra. The width of the penumbra is $\frac{100}{108}$ feet, or about 11 inches. On the pavement the width may be increased to 15 inches or more. Perhaps of all memories of New York we might bring back the great width of the penumbras of tall buildings. If we could see the shadow of a 1000-foot skyscraper cast on the ground below we should see a penumbra ten times as wide as that of a 100-foot building. On the pavement it might be 15 feet wide, or even more. There are ridges on the moon that have a height of 20,000 feet above the level plain below. The penumbras of their shadows must have a width of at least 200 feet, and probably more. It is sometimes said that moon shadows are sharp and this has been ascribed to the absence of atmosphere. We have seen that that cannot be true; the penumbra exists for the same reason that it does on the earth. But at the distance of the moon so small a width as a few hundred feet fades into insignificance, and the dense shadows appear to have sharp edges.

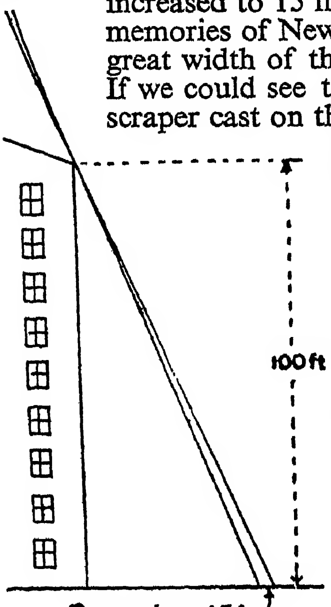


Fig. 49.

The Clouds of April

In April we often see small low clouds hurrying across the sky. We see their shadows scudding along over hill

and dale and across meadows. It is one of the prettiest effects of April weather, and for beauty and variety there are no weather effects to be compared with those of April. At other times there seem to be no clearly defined cloud shadows. It is usually only the low, dense, sharp-edged clouds of April whose shadows can be followed across the landscape. High up clouds are less dense, and they have jagged edges, so that there are no definite lines round their shadows. The shadows are big, perhaps miles long, so that we do not see small separate shadows like those of April clouds. As these clouds are high up they have wide penumbras. A cloud 10,000 feet up has a penumbra ten times as wide as that of a 1000-foot skyscraper; it may be 30 yards or more across. So we have shadows that are very big, and less dense than April cloud shadows. These shadows have indefinite edges, and beyond these edges wide penumbras. When such a cloud comes between us and the sun there is a rapid but gradual darkening, and we do not see a clear floating shadow. High up on the mountains, however, where he looked down on flat lowlands, Stevenson observed " clouds that travelled forth upon the sluggish wind and trailed their purple shadows on the plain ".

Shadows without Penumbras

There is another cloud effect belonging peculiarly to April. When small dense clouds are scudding across the sky we sometimes see the shadow of a window-bar suddenly become sharp and clear, with no appreciable penumbra. A moment later we see the shadow equally sharp, but a short distance away. A glance at the sun when this is happening is sufficient to explain the reason. A small dense cloud is floating across the sun. For a moment a small part only of the sun, near the rim, is uncovered. That bright part casts a shadow that is sharply defined, almost free from penumbra, because its width is small. A second or two later the cloud has moved on and left a small part of the sun exposed at the opposite rim. Again we get a clear sharp shadow. The shift of the shadow is due to light coming from opposite

points on the sun's rim, which are half a degree apart. In Fig. 50 the upper rim of the sun casts a shadow at A; the lower rim casts a shadow at B. If the distance AX happens to be about three yards, then the shadow shifts more than an inch. (The angle AXB should be half a degree.)

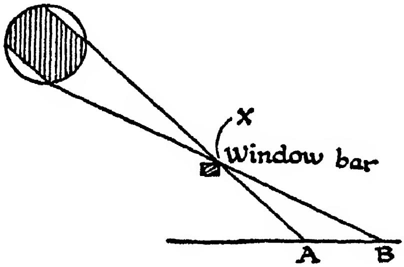


Fig. 50.

When an eclipse of the sun has almost reached the stage of totality, shadows stand out clear and definite, almost entirely shorn of their penumbras. At that stage the moon is doing at some length what April clouds do for an odd second or two: it covers up all but a small width of the sun and so reduces the penumbras almost to nothing.

A Shadow on the Retina

If we can throw a shadow on the retina, then we should expect a rather odd result. The shadow would be the right way up, and not upside down like the image produced by the eye lens. So we should see the shadow upside down.

The shadow has to be a small one; we can produce a sufficiently small one with a pin and a sheet of paper. We make a pinhole in the paper, and hold it close up to the eye. We hold the pin between the paper and the eye, and we move it about till we get the head of the pin between the pinhole and the eye. And sure enough, we see the head of the pin upside down in the pinhole.

Coloured Shadows

What colour is a shadow? Most people would say black, or at least black over the colours of the surface on which the shadow falls. We have a sort of feeling that shadows are black and we see them black; we let our prejudice affect our observation. As soon as we begin

to observe intelligently we see at once that shadows are not black; they are often dark, but they are not black.

Perhaps the most truly black shadow is the earth's umbra falling on the moon. During a lunar eclipse the dark side of the earth is turned to the moon, so that there is little light reflected from the earth. The little lights of human streets and dwellings are lost over an immense distance. But even this shadow is not truly black. The unwinking stars throw their faint light on the obscured lunar landscape; and the sun's light is refracted into the shadow by the earth's atmosphere.

In the early morning, on days when it is just too dark to see clearly enough for shaving, I switch on the light in the bathroom. The electric light throws a shadow of the lowest bar of the half-open window on the sill. The shadow is bright blue! The effect is most striking, as soon as one observes it. Yet no one does observe it until it is pointed out. I must have seen it hundreds of times without observing the blue colour. Indeed I did not observe it until I set myself definitely to look for coloured shadows.

An Experiment with Coloured Shadows

There is a very pretty experiment with coloured shadows which requires no special apparatus except a few small sheets of coloured glass or celluloid. We place a sheet of white paper on a table so that the sun shines on it. We fix a sheet of coloured glass upright, and look for the coloured patch behind it. We hold a pencil or other small object upright behind the glass. The shadow of the pencil is coloured. When we use red glass the shadow is blue-green; when we use blue glass, the shadow is yellow; purple glass gives a bright green shadow.

There has been some doubt about why these shadows should be coloured, but this experiment shows that the colours are subjective and not objective. That is to say they exist only in the eyes that see them. The decisive point is that when we first look at them, the shadows are not highly coloured, but the colours increase in brilliance as we go on looking at them.

The colours of the shadows are in fact complementary to the colours of the background. That is, each is the colour which makes up white when combined with the background colour.

Another Method

The following experiment can most conveniently be performed by means of two electric torches. Place tissue paper over the glass, and colour one piece red with a good poster colour. Fix up a white paper screen in a darkened room, and shine both torches on the same part of the screen. It may be necessary to draw the white torch farther back in order that it shall not swamp the red one. When an object is held between the red light and the screen it will cast a bright blue-green shadow, especially if it is held in such a way that the shadow is illuminated by the white light.

I found on trying this experiment that red light gave the best shadows, though I got an almost equally good yellow one from a blue light. Blue-green gave a less satisfactory red, and yellow gave a vague sort of blue. A good deal depends on the quality of the pigments used to colour the tissue paper. The white light is essential in this experiment; without it the shadows will be very nearly black.

Shadows amongst Leaves

Sometimes we get coloured shadows by reflection. A blue sky overhead spreads a blue tint over everything below it, and this tint is often most easily observed in shadows. But the most interesting shadows are those cast by coloured light. We often find such shadows amongst the leaves of trees. The source of the coloured light is not hard to find. When the sun is shining on a tree we look at the leaves from below, looking toward the sun. The leaves appear a brilliant green; green light is passing through them. The white light which is necessary for these coloured shadows is either direct or diffused sunlight. Sometimes the shadows amongst leaves are dark russet; but there are many variants. In spring,

for example, there is apt to be a lot of red in leaves and twigs, and we may find blues and purples amongst the shadows.

One summer evening I was coming home on the bus, and I was looking at the newspaper which I held almost flat. Along the top edge there was a bright, almost pink shadow. I looked for the reason. The back of the seat in front was painted apple green; the sun was shining horizontally on it, and the reflected green light cast the pink shadow.

The Red Shadow of the Ancient Mariner

I have often wondered about the red shadow of the Ancient Mariner's ship:

> But where the ship's huge shadow lay,
> The charmèd water burnt alway
> A still and awful red.

Why should the shadow be red? I suggest that the water itself may have been red. In the shadow of the ship it would be possible to see much more clearly into the water than outside the shadow, where the water would be screened by the reflected glare from the surface. Beyond the shadow the Ancient Mariner saw only surface phenomena, " like April hoar frost spread ". Within the shadow, things in the sea were not so obscured.

> Beyond the shadow of the ship
> I watched the water snakes:
> They moved in tracks of shining white,
> And when they reared the elfish light
> Fell off in hoary flakes.
>
> Within the shadow of the ship
> I watched their rich attire:
> Blue, glossy green, and velvet black,
> They coiled and swam, and every track
> Was a flash of golden fire.

CHAPTER VII

COLOURS

(Try to answer these questions first)

Where does colour vision begin?
What are the rainbow colours?
What is Newton's disk?
What is a complementary colour?
What are the complementary colours of red? blue? green?
How can complementary colours be formed?
What are the primary colours?
Why do blue and yellow pigments give green?
What are colour filters?
How is a spectroscope used?
What are the characteristic colours of sodium? strontium? barium?
What kinds of material are needed in fireworks?
What is an emission spectrum?
How does it differ from an absorption spectrum?
Which element was discovered first in the sun?

I READ somewhere a story of a man who went into a country where there were twenty-four primary colours. That was indeed an odd thing to happen, even in fairy-land, because colour is a subjective thing: it depends on the eyes of the one who sees. Light is alike to all, and falls alike on all eyes; but all eyes do not see alike. When my own eyes were examined I found out that one of them sees a rather brighter world than the other, and I like to keep the optimistic eye wide open.

The perception of colour starts with the cones, the nerve endings in the fovea or middle part of the retina. Cones respond to certain wave-lengths, and the brain interprets the responses as differences of colour. There are said to be people so colour blind that they have no sense of colour at all; something is missing from the nerve endings. Their world is a world of greys, approximating to white on the one side and to black on the other. Such unfortunate people must need great courage to face the world with cheerfulness. We depend so much on colour for brightness. A burst of yellow jasmine is a cheering thing in the depth of winter; golden crocuses are like spring come suddenly to life; and all through the year nature cheers us with a background of a thousand varied greens, setting off splashes of reds and yellows and blues and all the mingled colours.

Wordsworth's heart leaped up when he beheld a rainbow in the sky, and whose has not? Whose, that has the whole range of colour sense?

The Colour Disk

The rainbow colours are: red, orange, yellow, green, blue, violet. We know that these colours are not unrelated; we have seen that each colour has its own wave-length and that the colour depends on the wave-length. Newton used a very simple method for combining colours. To imitate his method we want a circular piece of white cardboard, about 4 or 5 inches across. If there is any difficulty about obtaining a good white we can paste white paper on any coloured board; it is well to paste paper on both sides, so as to check buckling, and to let it dry under pressure. Divide the circle into six sectors, and then each sector into three (Fig. 51). Use the clearest and brightest colours you can get; artists' colourmen sell ranges of "spectrum colours" which do very well. Paint the sectors red, orange, yellow, green, blue, violet, and then repeat till all the sectors are coloured.

When the colour disk is ready, push a nail through the centre and set it spinning by flicking the edge. The eyes hold the colours for a small fraction of a second, and so combine them. The bright rainbow colours combine to give white. It may be a rather dirty white, but it is near enough to white to show the effect of combining

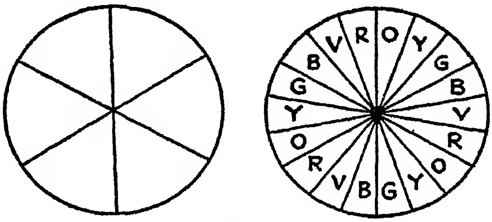


Fig. 51.

the colours. There are several reasons why the colour is not a true white. The colours are not pure spectrum colours. The disk absorbs most of the light that falls on it; the red, for example, reflects little but red light, and absorbs the other colours; so that we get a greatly reduced amount of light from the disk as a whole. And it is highly improbable that we should get the colours in the same proportions as they occur in white light.

Complementary Colours

We can use the colour disk in other ways. We can divide it into five sectors instead of six, and paint the sectors with the rainbow colours except red. When we spin the disk we get a blue-green colour. If we put back the red we get white once more. So that blue-green and red, when combined in the proper proportions, give white. Red and blue-green are said to be complementary colours—that is, together they give white. There is another simple way of combining two colours (Fig. 52). We paint squares of white paper, one with each colour,

and we place them on a table. We hold a sheet of plain glass halfway between the two colours. If we are testing red and another colour, it is usually better to have the red in front of the glass because the red is probably the brighter

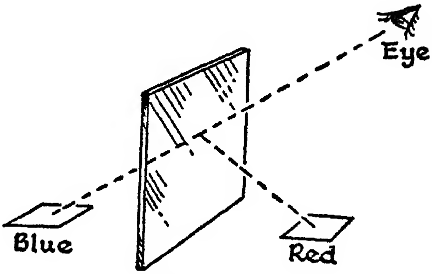


Fig. 52.

colour. We stand at the side of the glass from which light comes, and we look down through the glass at the colour behind it. We should see in the same spot the reflection of the colour in front of the glass, but a little adjustment may be necessary. When we combine red and blue-green in this way we get a near approach to white.

After-images

We can get complementary colours simply by staring. We stare at a sheet of brightly coloured red paper or cloth for a minute or so, until the eyes are fatigued. Then we look aside at a sheet of white paper, and we see on it the complementary blue-green. The explanation is that the nerves in the retina which give the sensation of red are so greatly fatigued that they no longer respond to red; for a few moments we are red-blind. The white paper reflects to our eyes all the rainbow colours, and all these colours affect the retina except red. So we see the colour which is composed of all the rainbow colours except the red. That is, we see the colour complementary to red.

The patches of the complementary colour which we

see after a prolonged stare at a bright colour are called *after-images*. I was looking out of a brightly lit window the other day when a friend came between my eyes and the window. For some seconds I saw his face completely black; my eyes were fatigued to all colours. We sometimes get dark after-images after staring at a fire, or after a quick glance at the sun.

Red and blue-green are not the only pair of complementary colours. When the eyes are fatigued by staring at any bright colour we are apt to see its complementary colour as an after-image. One of the most surprising pairs of complementary colours is blue and yellow. If we combine them on a colour disk we should get a near approach to white. Or we can use a sheet of glass to place the reflection of blue over yellow. Another pair of complementaries is green and magenta.

Primary Colours

There are three colours which cannot be made by mixing other colours, and which are therefore called *primary colours*. They are red, blue, and yellow. (We

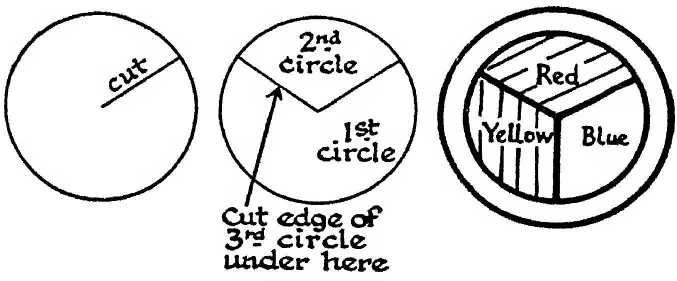


Fig. 53.

had better say now that the mixing of two pigments is a different thing from mixing the reflected light from two pigments. We can forget the actual pigments for the present, and think only of the reflected light.)

There is a convenient way of mixing the primary

colours in varying proportions. We want three equal circles of white paper; the radius may be 2 inches (Fig. 53). We cut a narrow slit in each from the circumference to the centre. We paint one circle bright red, another bright blue, and the third bright green. We slip the cut edge of one circle through the slit in another, and then the cut edge of the third circle under the slit in the second. We mount the three circles on a thin nail as an axle, with a rather bigger circle of cardboard behind them. We can fix the circles so as to show various proportions of the three primary colours, and then hold them in place with small pins.

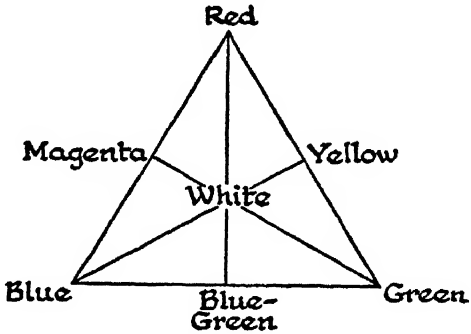


Fig. 54.

We set the card spinning by flicking it, and so we combine the colours. Some of the results of combining two colours or three may be deduced from Fig. 54, the colour triangle. The three primaries are placed at the corners. Halfway along each side is placed the colour produced by combining equal quantities of the colours between which it lies; yellow, for example, is made by combining equal quantities of red and green. Equal quantities of red, blue and green give white. Two parts of blue and one of yellow give white, and so on. The spinning disks do not actually give white but a light grey.

By uncovering various amounts of the three primaries we can get a great variety of colours.

Mixing Pigments

We get quite different results when we mix pigments. When we mix light from blue and yellow surfaces we get white, but when we mix blue and yellow pigments we get green. The reason for the difference lies in the means

by which the colours are produced. When white light falls on a blue pigment, the pigment absorbs reds and yellows; it reflects blue and also some green. A yellow pigment absorbs blue and violet; it reflects yellow, and also some red and green which are the colours nearest to it in the spectrum, or range of rainbow colours. When the two pigments are mixed it may be seen that all the colours are absorbed by one or other of the components except green. And so the mixture gives green.

The mixture of any two pigments gives only the colours which are not absorbed by either of the components. The result of mixing several pigments is usually a muddy colour, because most of the light that falls on the mixture is absorbed by one or other of the components, and very little of it is reflected.

Colour Filters

We have already seen that pieces of coloured glass can be used as colour filters. A piece of ruby glass, for example, is transparent to red light, but it stops nearly the whole of the other colours. Tinted celluloid also can be used in this way. But we need deep colours to get good results. A piece of lightly tinted red glass certainly lets through a bigger proportion of red light than of any of the other colours, but it lets through too much of the other colours to be a good filter.

Let us look through a good red filter, either glass or celluloid. We look out at a red world; there appear to be only two colours, red and black. Every surface that reflects red light looks red. A truly red surface looks very red indeed. White surfaces reflect all the colours, including red; the red filter stops all the colours except red, and so we see white surfaces red. Yellow surfaces reflect some red, as well as yellow, and so we see them red. But it is not nearly so clear a red as we get from red and white surfaces; there is a lot of black in it, because the filter stops most of the yellow light. Green and blue surfaces look almost entirely black. They reflect little but green and blue light; these colours are stopped

by the filter, little light gets through to the eyes, and so the surfaces look black.

We sometimes find red in unexpected places. Young foliage often contains a lot of red. Young leaves often look whitish, and these appear red when a red filter is used.

Invisible Red

I have been looking through a red colour filter at a magazine cover printed with a design in red and green. The effect was surprising. The red parts of the design simply disappeared; they merged with the surrounding white. The green parts of the design were almost completely black.

People sometimes wear red goggles, and they find their eyes adapt themselves in a remarkable way; after a short time they begin to interpret the prevailing red as the normal white. The red London buses, for example, appear to be white. Even the red of the magazine cover seemed to be doing its best to look white; it certainly had not the striking appearance that it had when seen without the filter.

I have observed the same kind of effect when working under mercury vapour lamps. Newcomers always exclaimed at the greeny-yellow appearance of people under the lamps; but after a day or two no one saw anything unusual: people just looked normal. We had learned to interpret the unusual background as normal, that is, as if it were whitish. I have been told the same sort of thing also by people who have had their eyes operated on for cataract. At first they see a red or blue background—some see it red, and some blue. Those who see red find it impossible to play cards because the red pips are invisible. But the effect soon wears off, and they see the normal white, red, and blue.

Other Colour Filters

In a set of colour filters the red is usually the best. The blue filter usually lets through a lot of green light as well as blue. White and blue, of course, both look

blue when seen through a blue filter. Green looks almost as green as without it, but not quite—the green is darker, and this shows that some of the green light has been stopped. Red and orange look black, as one would expect, but a sheet of pink blotting paper looks blue. The reason for the latter colour is that pink is red with more or less white added to it; the blue is the blue of the white. Yellow looks definitely green, and this shows how much green there is in yellow pigments.

Under a green filter white and green both look green; there is no observable difference between them. A very little red comes through the filter, and red has the appearance of dark brown. Blues look definitely green, so that there is a lot of green in blue pigments.

The least satisfactory of the colour filters is the yellow one. It certainly accentuates yellows, and makes white appear yellow. But reds are little changed by it, and blues appear green-blue.

There is an interesting point about the thickness of colour filters. Suppose a twentieth of an inch thickness allows 9-tenths of green light to pass through. The next twentieth allows 9-tenths of this 9-tenths to pass through; that is $\cdot 9^2$, or $\cdot 81$. Suppose the same glass, a twentieth of an inch thick, allows a quarter of red light to pass through. The next twentieth allows a quarter of a quarter, or only a sixteenth. By doubling the thickness we greatly increase the efficiency of the filter.

The effect is still more striking if we increase the thickness to a quarter of an inch, or 5-twentieths. The proportion of green which comes through is $\cdot 9^5$, or $\cdot 59$; we get just about 3-fifths of green light. The proportion of red is $\cdot 25^5$, or about 1-thousandth; so that the filter is almost opaque to red light.

Two Eyes see as One

Let us hold a blue filter in front of one eye, and a yellow filter in front of the other. We look at a white surface. We close one eye and see the surface yellow; we close the other eye and see it blue. When we open both eyes, there is a flicker of adjustment, and then we

see the surface white. The white is not so brilliant as without the filters, because part of the light is suppressed, but the brain does combine the two colours, seen separately by the two eyes, so as to give the combined effect of white. The adjustment is not perfect. At one moment we may see yellow and at another blue, but we do also get the combined effect of white.

We can get similar effects with red and blue-green which combine to give white; and with red and green which combine to give yellow.

Characteristic Colours

We know that we can get a yellow flame by heating common salt in the blue gas flame. This flame is characteristic of the metal sodium. We get the same colour from other salts which contain sodium, washing soda and baking soda (bicarbonate of soda), for example.

Other metals have their characteristic colours. Salts of strontium give a bright red flame when they are heated in the blue gas flame; salts of barium give a green flame. Chemists use these colours, in the "flame test", as a test for the presence of certain metals. They dip a wire, preferably a platinum wire cleaned with hydrochloric acid, in a solution of the salt to be tested, and hold it in the flame. The colour of the flame may confirm the presence of a particular metal.

Coloured Flames

Firework makers are greatly interested in the production of coloured flames. When they are looking for a coloured fire they want at least three things: something that will burn, in order to keep the fire going; something to supply oxygen, so that the stuff may burn strongly; something to colour the flames. The things most commonly used for the fire are lampblack, or finely powdered charcoal, flowers of sulphur, and sometimes powdered shellac. The salts used to supply oxygen are usually nitrates and chlorates. We also want a metallic salt to supply the colour; if we use the nitrate or chlorate, the

salt serves the double purpose of supplying both oxygen and colour. These three kinds of material are essential. Sometimes other things are put into the mixture, usually to give some kind of sparkling effect. Fine sawdust may be used, or fine steel filings, or iron filings, or magnesium powder. Each of these gives a distinctive kind of spark.

The metal strontium gives a crimson colour to flames, so it can be used for crimson fire; strontium nitrate is used. Barium nitrate is used to give a green colour to flames. Powdered antimony gives a brilliant white flame.

The Effect of a Glass Prism

When we look through a triangular glass prism we see objects fringed with the rainbow, or spectrum, colours. We can get a better effect by admitting sunlight to a dark room through a narrow slit (Fig. 55). We use a small mirror to throw the beam horizontally across the room. We place the glass prism so that the beam of light falls on one of its faces. We hold a sheet of paper on the far side of the prism so as to receive the light that comes through. The white sunlight is spread out into a spectrum.

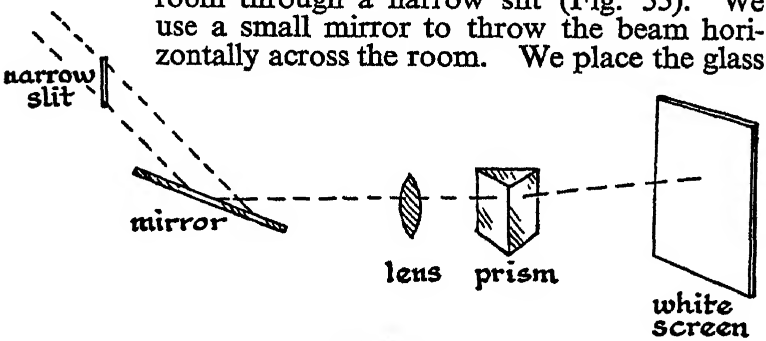


Fig. 55.

We can improve the spectrum by placing a lens between the slit and the prism, so as to focus the light on the prism. We can still further improve it by rotating the prism slowly till we get the clearest colours.

It is interesting to hold the colour filters, one by one, in front of the slit through which light enters. We can

then see the range of colours which actually comes through each filter. The red filter, for example, should show a bright red spectrum, a little yellow, and very little else.

Even without having a dark room we can test the colour filters. We look through the prism at an electric lamp, and we hold the filters in turn between the lamp and the prism. We have to hold the prism so that we see the spectrum, and then adjust the filter so that it shuts off part of the light.

The Spectroscope

We can see that light rays are bent as they enter and leave the prism; they are bent twice toward the base of the prism (Fig. 56). The amount of bending depends on the wave-length. The comparatively long red rays are bent least, and the very short blue rays are bent most.

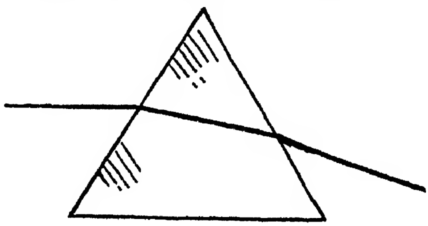


Fig. 56.

The spectroscope is an instrument for examining light which has been spread out into colour, or wave-lengths, in passing through a glass prism or a diffraction grating. Heated sodium vapour gives out light which is almost entirely yellow; the spectrum consists of two narrow bands of yellow close together. The presence of these bands in a spectrum shows the presence of sodium in the heated substance from which light comes. Other elements also have their characteristic spectra, so that we can use the spectrum to detect which metals are present in a sample of ore. The ore is strongly heated, and the light which it gives is examined through a spectroscope. The spectrum is photographed, so that it can be studied

at leisure. A scale enables the positions of the bands of colour to be fixed exactly.

Metallurgists use this method of analysing ores as part of their usual technique. The method is quicker and more certain than ordinary chemical analysis, especially when only traces of elements are present. The brightness of the lines indicates the amount of each element.

Lines in the Spectrum

Light from an electric lamp gives a continuous spectrum ranging through the rainbow colours without breaks. In some spectra, however, there are dark lines or bands. We know that strongly heated sodium gives out yellow light of two wave-lengths which are nearly equal. If white light is passed through less strongly heated sodium vapour, the vapour absorbs just these wave-lengths, and lets the rest of the light pass through; it is transparent to nearly all visible light except light of these two wave-lengths. We pass white light through cooler sodium vapour, and then spread it out into a spectrum. We get a continuous spectrum except for two narrow dark bands where the sodium yellow should come. Other elements also absorb light of the same wave-lengths as those they emit. So we have two kinds of spectra: the coloured *emission* spectra given by heated vapours; and the *absorption* spectra with dark lines, given by white light which has passed through less heated vapours.

The sun is an extremely hot body surrounded by an atmosphere of less highly heated vapours. White light from the sun's surface passes through these heated vapours before it reaches us; many wave-lengths are absorbed by the sun's atmosphere, and there is a dark line in the spectrum for each wave-length that has been absorbed. The thrilling thing is that these dark lines tell us which elements are present in the sun's atmosphere.

It turned out that the lines in the sun's spectrum represented elements already known on the earth, except for one small group of lines which were ascribed to a hitherto

undetected element. This element was called *helium* (from *helios*, the sun); it is now known as one of the rarer gases in the earth's atmosphere.

Spectrum analysis has been extended to the remote stars, so that we now know something about their composition. It has told us something also about the atmospheres of the planets. Sunlight falling on the surface of a planet is reflected back to us through the planet's atmosphere. A comparison with the usual solar spectrum gives an indication of what is present in that atmosphere.

CHAPTER VIII

HOW LIGHT IS REFLECTED

(Try to answer these questions first)

Why are some surfaces dull black?
How is a household mirror made?
How far back is the image in a mirror?
Why can words on blotting paper be read in a mirror?
When do we see reflections in plain glass?
How can a sheet of notepaper be made to give a clear reflection?
How can mirrors be used to see the back of one's head?
How does a periscope work?
What is an autocollimator?
How does a kaleidoscope work?
Why are mirrors often placed on the walls of restaurants?
How are mirrors used in measuring?
What is the cause of twilight?
How is a sextant used?
Why can we often see through windows in one direction only?
Why is the sky black when seen from great heights?
Why is the water black in mid-Atlantic?

A BEAM of light falls on an opaque surface. Any one of various things may happen. The energy of the beam of light may be changed, but it cannot just disappear.

If the surface is dull black almost the whole of the

beam of light may be absorbed by it. The energy of the light is taken up by the molecules of the black surface; the molecules move a little more quickly, and so the material is a little warmer. The surface looks black because it sends little or no light to the eyes.

Something quite different happens on a smooth or polished surface. A little of the light may be absorbed, but most of it is reflected. As soon as we begin to look for them we can find any number of smooth and polished surfaces that reflect light. Well-polished furniture gives clear reflections, sometimes almost as clear as those given by a mirror; polished metal shines brilliantly by the light it reflects; the glaze on china-ware is another good reflector. Mirrors, which are intended to reflect as much light as possible, used to be made of polished metal. Very good mirrors are made by coating the surfaces of sheets of glass with silver, and then polishing the silver; the front (silvered) surfaces of these mirrors are used. Household mirrors are coated at the back of the glass with silver and mercury, the coating being covered with red-lead paint to protect it from injury. Stainless steel makes excellent mirrors and is coming into use for this purpose.

Mirror Images

We get our first ideas of reflection when we look at a mirror. We see our face apparently behind the surface of the mirror, and reproduced point for point. Light reflected from the face falls on the mirror; the mirror reflects it back, so that some of it enters the eyes and forms an image on the retina.

Touch the mirror with a finger. The mirror finger comes up to touch the real finger. Draw the finger back, and the mirror finger recedes, so that the image is always as far behind the mirror as the finger is in front. We can always find the position of a point on a mirror image by measuring as far back, at right angles to the mirror, as the object is in front. In Fig. 57 AB is a mirror. $CX = C_1X$, $DY = D_1Y$, and $EZ = E_1Z$. $C_1D_1E_1$ is the mirror

image of CDE. And CDE is the mirror image of $C_1D_1E_1$.

In Fig. 58 we have the word AND and its reflection. We copy the reflection carefully and hold it in front of

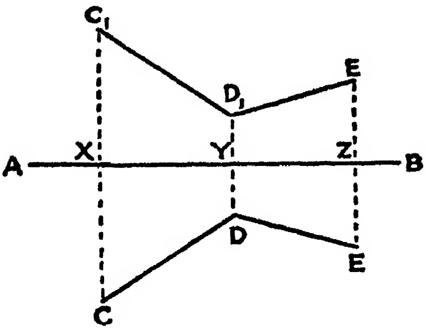


Fig. 57.

the mirror. The reflection is the shape of the original AND. A reflection of a reflection takes us back to the original shape.

We write a few words in ink, and at once blot what we have written. The blotting paper holds a kind of reflection of what we have written; each point on the blotting paper is exactly in front of the corresponding point in the writing, just as the reflection is. We hold the blotting paper in front of a mirror and we can then read what is on it. Villains in detective stories used to be very careless about blotting their incriminating letters, so that the detective had only to hold the blotting paper up to a mirror in order to find out what they had been up to. Nowadays it is a clean sheet of blotting paper that sets the detective thinking and suspecting. He wants to know why the letter was *not* blotted.

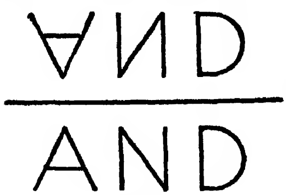


Fig. 58.

A Mirror Game

Here is an amusing trick with reflections. We fix a small mirror upright on a table (Fig. 59), and in front of it we put a sheet of paper. We mark two points on the paper, one near the mirror at one side, and the other farther back at the other side. We look steadily in the mirror, put the point of a pencil on one dot, and try to draw, slowly, a straight line joining the two dots. The merest glance at the real dots on the paper is sufficient to spoil the trick. If we keep the eyes strictly on the mirror images, it is quite difficult to draw the line because the hand persists in moving in the wrong direction.

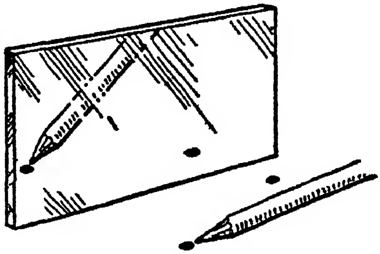


Fig. 59.

A variant of this trick is to write your signature whilst looking steadily at the pencil in the mirror. When you have succeeded you will probably find that you have written it backward.

Reflections in Glass

The smooth surface of a sheet of glass reflects part of the light that falls on it, though most of it passes through. When we hold a sheet of glass up to the light we do not see a reflection, because the reflection is swamped by the light coming through. We get quite a good reflection in the glass when we hold it in front of a dark surface. In the daytime most light enters the house from outside; the interior is comparatively dark. In these conditions we see reflections on the outsides of windows, but not so clearly on the insides. At night the windows of a lighted room give good reflections on the inside but not on the outside. It is a point always to keep in mind that when we want a reflection from the surface of a transparent material

we have to turn it away from the light, that is, so as to have the darker side behind it.

Light just grazing Surfaces

The smooth surface of water is another good reflector. Reflections in the still water of canals and ponds and slow-moving rivers are especially good because the reflected light comes up to the eyes at a small angle. Light that just grazes the surface will sometimes give clear reflections when light falling at a steeper angle does not. Notepaper has a smooth surface, but not smooth enough to serve as a mirror in ordinary conditions. We can, however, get the reflection of a lighted candle, or of a lamp, from notepaper. Hold a sheet of paper on a level with the flame or glowing filament, and look across the surface of the paper: a clear reflection may be seen. We can indeed get clear reflections from what are apparently most unpromising surfaces. Glazed tiles round a fire-place show no signs of a reflection until I bring my eyes close to the surface. As the eyes approach there is a faint, indefinite reflection; the reflection gets clearer and more definite as the eyes get closer to the surface of the tiles.

Sometimes we see remarkable reflections in the windows of buses. The window just at our elbow gives only a feeble reflection; the light which reaches our eyes is reflected at right angles to the glass. Only when it is dark outside do we get at all a good reflection from this window. But farther down the bus the windows give reflections that are almost as clear as those from mirrors; the light from these distant windows grazes the surface as it travels to our eyes. It is interesting, too, to see how the reflection brightens when we pass a dark surface, and almost fades away when we pass a sunny surface.

In the morning and in the evening the windows of houses are sometimes lit up with a bright glare. This is not a grazing reflection of the sun's rays, but usually a reflection more or less perpendicular to the surfaces of the windows. When the sun is higher in the sky the reflected rays are thrown downward, and do not reach

the eyes of observers. It is only when they are thrown back horizontally that we see them.

Pretty Geometry

There is a very pretty bit of geometry connected with reflections (Fig. 60). Draw the line AB to represent a mirror; C is a dot near the mirror. Draw a line CD to represent a ray of light from C to the mirror. Very carefully we make angle EDB equal to angle CDA. DE is the reflected ray; an eye at E sees the dot C back along

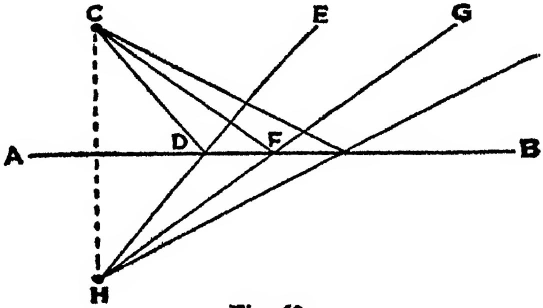


Fig. 60.

the line ED. CF is another ray, and FG is the reflected ray (angle GFB = angle CFA); so the dot C is seen back along GF. We can draw other rays in the same way. If the work is carefully done, all the reflected rays meet at the same point H. H is the position of the mirror image.

H is as far behind the mirror as C is in front of it. We can always find the position of the reflection of a point by drawing a line from it at right angles to the mirror, and measuring back as far as the point is in front

The Barber's Mirrors

When the barber has exercised his skilled craft upon our hair, he usually lets us see what he has done to the back of the head. He needs two mirrors for that. There is the big mirror in front, and the barber holds a small mirror behind the head and a little to one side. Light

from the back of the head falls on the small mirror; this mirror reflects it to the large mirror, and the large mirror reflects it to our eyes. We see the back of our head by means of light reflected twice. A lady inspects her back hair in very much the same way. The tailor lets us see what the man walking behind sees, by means of a double reflection, so that we can go forth with mind at ease, without fear of offending the neighbourhood by a coat fitting badly at the back.

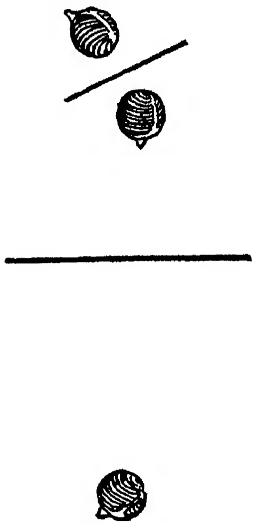


Fig. 61.

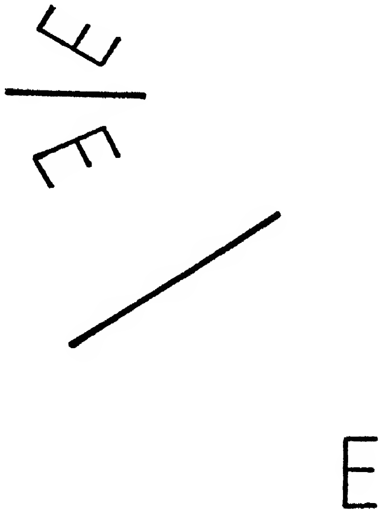


Fig. 62.

Fig. 61 shows how an image is formed in the small mirror and then in the large one. The large mirror forms an image of the object in the small one just as if the latter were a real object. We are looking down on the man who has just had his hair cut. The image of the back of the head in the big mirror is just as far behind this mirror as the image in the small mirror is in front of it. The image of the face in the big mirror has been omitted; we do not look at it.

Fig. 62 illustrates an interesting experiment to confirm

this idea. We draw two straight lines to represent mirrors, one large, one small, facing inward. Between them we draw the letter E. We get the image of this letter in the smaller mirror by drawing, at right angles from each angular point, and then measuring as far back from each point as the real point is in front of the mirror. We get the second reflection, in the large mirror, by treating the first reflection as if it were a real object. If we now set up mirrors along the two lines, we shall find the reflections just as we had predicted.

The Periscope

The simplest kind of periscope is an arrangement of two mirrors, to give a double reflection. The mirror A in Fig. 63 faces to the right. Light from a scene in front is reflected at A, down to the mirror B which faces to the left. It is reflected again at B, so that an observer at C sees the scene in the direction CD. By means of a periscope of this kind a soldier can see over the top of a trench without exposing himself. The two mirrors are set at 45°, so that the scene appears in the true direction, but lower than it actually is. The periscopes used on submarines are more elaborate than this simple one.

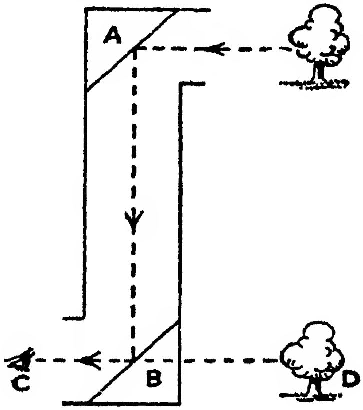


Fig. 63.

With two small mirrors and a large sheet of cardboard we can make a periscope. On the cardboard we rule out four strips, each as long as possible and each the width of the mirrors (Fig. 64). We draw the sloping lines on the other side of the card. We cut out the shaded squares, score with a knife along the lines, and then fold along the lines. We join the edges, to form a square tube, with passe-partout or paper and paste. The sloping lines give

the positions of the mirrors. These both face inward along the tube; they may be fixed in place with strips of adhesive tape or pasted paper. When the periscope is complete we can use it to perform the impossible feat of seeing through a brick wall.

Mirrors at Right Angles

At a corner of a cardboard box we have three surfaces, each at right angles to the other two. We can cut away two sides of the box, retaining the other two sides and the base (Fig. 65). We fix two small mirrors so that they meet at the angle made by the two sides; we can hold them in place with spots of gum. With this simple apparatus we can get several interesting effects. We make a dot on the third surface. Instantly we get the reflections in the two mirrors, and we see the space round the line where the mirrors meet divided into four quadrants. In the fourth quadrant there is a dimmer image of the dot; this is caused by a double reflection, from each mirror in turn. We draw letters or other shapes and see their images. Fig. 66 shows the reflections of a letter F. The second reflection (*c*) may be regarded as the reflection of either of the first reflections (*a* or *b*).

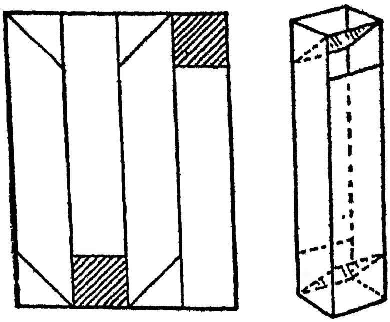


Fig. 64.

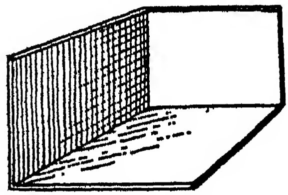


Fig. 65.

We hold the two mirrors on a level with the face, and see our reflection in them. We rotate the mirrors, keeping the line where they meet upright, and we find an extraordinary thing: the image of our face does not move.

We close one eye; the image of the open eye is bisected by the line where the mirrors join, and there it remains whilst we rotate the mirrors about an upright axis. In Fig. 67, A is the position of the eye of an observer. B and

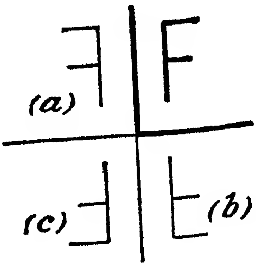


Fig. 66.

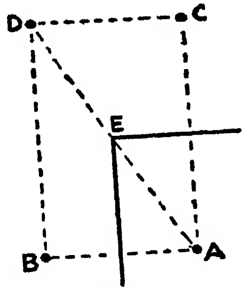


Fig. 67.

C are the positions of the first reflections; D is the second reflection. It is easy to see that AED is a straight line, and that ED equals EA. It is the second image, at D, that we are looking at, and its position does not change so long as A and E do not change.

The Autocollimator

We can get still more remarkable effects by fixing a third mirror at right angles to each of the other two, that is, on the third cardboard surface. We hold the mirrors turned to the face, and we see the reflection of the face; its position does not change however we tilt the mirrors. We close one eye, and the reflection of the open eye is always at the point where the three mirrors meet. We are actually looking at a third reflection; light is reflected from each of the three mirrors in turn.

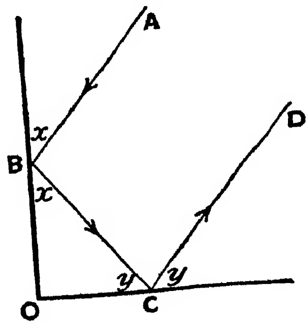


Fig. 68.

We hold the arrangement of three mirrors in a beam of

sunlight, and turn it this way and that. It gives no patches of reflected sunlight on walls or ceiling. The whole of the beam of sunlight which falls on the mirrors is thrown back parallel to the direction from which it comes. Anyone who likes geometry can see why this is by studying Fig. 68. AB is a ray of light falling on one of the mirrors; it is reflected along BC to the other mirror, and then along CD. So the angles marked x are equal, and also the angles marked y. Now OBC is a right-angled triangle, so $x + y =$ a right angle.

$$\begin{aligned}\angle ABC + \angle DCB &= 4 \text{ right angles} - 2x - 2y \\ &= 2 \text{ right angles.}\end{aligned}$$

And that is the condition that CD should be parallel to AB. If the ray were now to strike the third mirror, it would still be parallel to its original direction.

The arrangement of three mirrors at right angles is called an *autocollimator* because it automatically sends back rays parallel to rays which fall on it. Autocollimators have been used for picking up ships in the dark without revealing their presence to possible enemies. A searchlight beam sweeps the seas till it falls on an autocollimator. The return beam is seen only by men standing near the searchlight. They have also been used for fixing the position of tanks in the dark.

The Kaleidoscope

That pleasant little instrument, the kaleidoscope, consists essentially of two mirrors set at an angle of 60°. A third mirror gives increased brilliance. We can use slips of glass for the mirrors. A glass-cutter will cut three slips of glass 6 inches long and $1\frac{1}{2}$ inches wide. Join them with adhesive tape to form a triangular tube, then cover the outside of the glass with black or dark brown paper. On a sheet of white paper put some coloured beads, bits of twisted coloured tinfoil, and other small objects. If we look down at them through the tube we see patterns formed by reflections of the small objects; there are five reflections, plus the original group of objects. By slight movements of the objects we can get innumerable patterns.

We can replace one of the glass mirrors with a piece of cardboard. We get two first reflections, two rather duller second reflections, and a still duller third reflection (Fig. 69).

A rather more elaborate kaleidoscope may be made in the following way. We want three pieces of glass each 6 inches by 1½ inches; two pieces are tapered off at 45° at one end. We also want two glass triangles; one is equilateral with 1½-inch sides; the other is isosceles,

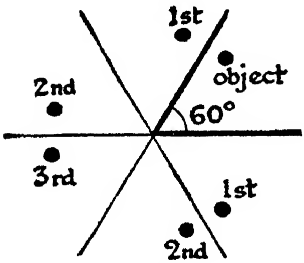


Fig. 69.

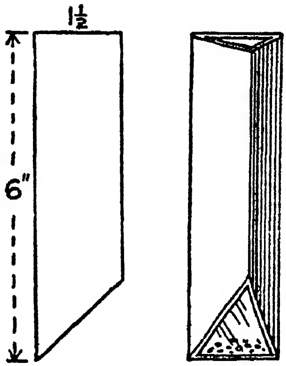


Fig. 70.

with 1½-inch base and the equal sides 2 inches. The three long pieces are joined with adhesive tape; the tapered ends come together (Fig. 70). The larger triangle is fixed over the tapered ends, and the equilateral triangle over the other end. Before putting on the second triangle beads and bits of coloured tinfoil should be dropped into the tube. The glass is covered, as before, with black or dark brown paper; the triangular ends are left uncovered. In using this kaleidoscope the sloping triangular end is turned to the light. A jerk will change the positions of the small objects, and the patterns.

Multiplying a Restaurant

Sometimes the walls of restaurants are covered with mirrors, with the effect that the apparent size of the room

is enormously increased. The room itself is reflected on four sides, with all its lights and tables and people, so that they are multiplied fivefold. Beyond these first reflections there are the dimmer second reflections, the still dimmer third reflections, and so on, till the reflections fade out.

The reason for the fading out is, of course, that no polished surface reflects all the light that falls on it. A good mirror may reflect 4-fifths of the light, so that a first reflection has 4-fifths of the brightness of the original scene. The second reflection is again 4-fifths, so that the brightness has $\frac{4}{5} \times \frac{4}{5} = \frac{16}{25}$ of the brightness of the original scene. The third reflection has $\frac{4}{5} \times \frac{4}{5} \times \frac{4}{5} = \frac{64}{125}$ of the brightness. And so we go on reducing the brightness $\frac{4}{5}$ at each stage. The brightness of the third reflection is about $\frac{1}{2}$, of the sixth reflection about $\frac{1}{4}$, of the ninth reflection about $\frac{1}{8}$, and so on. If the mirrors are not so good we may get no more than $\frac{2}{3}$ of the light reflected. The third reflection would have only $\frac{8}{27}$ of the brightness of the original, and that is less than a third. The sixth reflection would have less than a ninth, the ninth reflection less than a twenty-seventh, and so on. But even these lesser reflections would add brilliance to the scene, as proprietors of restaurants are well aware.

Lights between Mirrors

With two rather large mirrors we can get the same sort of effect. We place the mirrors facing each other, and stand between them. We see numerous reflections of ourselves, alternately front and back. Each reflection is less bright than the one in front of it, and the distant ones can only just be seen. A lighted candle gives an even more striking effect: the space between the mirrors is suddenly lit up with numerous candles. The light from distant reflections has been flung to and fro between the mirrors many times before it reaches the eyes.

We can get the effect also with a dressing-table mirror and a hand mirror. We sit at the table and hold the small mirror just above the eyes. We hold a lighted candle or match between the two mirrors. With a little adjustment we can see a long vista of candles lighting up a tunnel.

Doubling an Angle

We hold a small mirror in bright sunlight. It reflects the sunlight, and we see a bright patch of light on wall or ceiling. We turn the mirror very slightly, and the patch of reflected light moves a considerable distance. With a small tripod stand we can get an interesting and amusing effect. We put a small mirror on the tripod, and place it on the wrist with one of its feet resting on the pulse. We hold the wrist in bright sunlight, and keep it as steady as

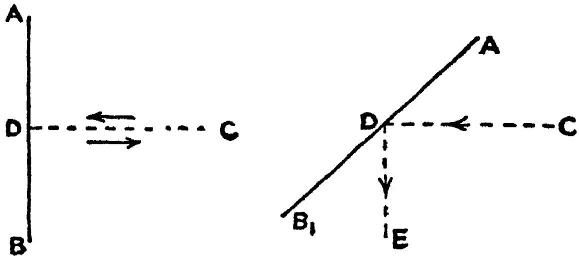


Fig. 71.

possible. We look for the patch of reflected sunlight. We see it dance on the ceiling, and we can count the pulse-beats, exaggerated by the reflected beam of light.

Scientists sometimes use the same method of exaggerating small movements; we remember how Foucault used a rotating mirror in measuring the speed of light. There is one thing we have to be careful about: if the mirror is turned through an angle of, say, 4°, the reflected ray is turned through an angle twice as great, 8° in this case. Fig. 71 shows a ray of light CD falling on a mirror AB; it is reflected back along DC. Then the mirror is turned through an angle of 45°; the ray CD is reflected along DE; that is, it is turned through an angle of 90°.

The Sextant

The sextant is a reflecting instrument used by navigators to find the height of the sun, moon and stars above the horizon. It has a small telescope, which the navigator points at the horizon (Fig. 72). It has two small mirrors.

One of them, A, is fixed at 45° in front of the telescope, but not blocking the view. The other, B, is fixed to a pointer; it can be rotated by moving the pointer. Light from a star falls on the upper mirror; it is reflected to the lower mirror, and again reflected to the telescope. The navigator moves the pointer, and with it the upper mirror, till the star appears on the horizon. The angle he wants to measure is CBD, which is the angular height of the star above the horizon. The position of the pointer

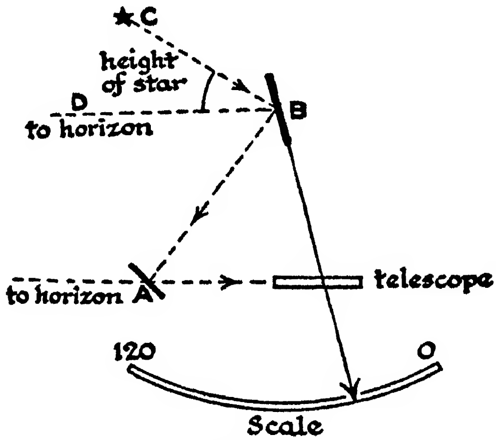


Fig. 72.

tells him how much he has had to rotate the mirror, say 17°. The ray from the star has been turned through double this angle, 34°. This is the angle CBD, the angular height of the star. The navigator does not have to double the angle he measures. That is already done on the instrument; the scale is divided into half degrees, and these are numbered as if they were degrees. When the index bar is at zero the two mirrors are parallel and the ray of light is not turned through an angle.

The sextant gets its name from the actual angle on the scale, which is 60°. In mathematics a sextant is the sixth part of a circle, or 60°.

Spreading out Flickers

Most people have seen the small red neon lamps that are used to give a little light when only a little light is wanted. And many people think that the light is steady; but a mirror can be used to show that it flickers. If we hold a hand mirror below the lamp and pass it rapidly to and fro, the image of the lamp is broken up into separate illuminated bulbs. The rapid movement exaggerates the flickers and shows up the gaps.

Diffused Reflection

Smooth and polished surfaces are exceptional; nearly all surfaces are more or less rough. Light falling on rough surfaces is scattered or diffused in all directions. It is the diffusion of light that makes objects visible, with the exception of bodies that emit light. Sunlight, shining through clouds, is diffused. We have all noticed the difference between the bright glare and dark shadows of direct sunlight, and the soft lights and shades of diffused daylight. The clouding effect is often imitated in lighting schemes. Lamp globes are frosted, or clouded with translucent material, which lets through diffused light.

The glare from an unshaded light can be both painful and harmful to the eyes. Such lights are not permitted in factories, which are subject to government supervision. Unfortunately they are often tolerated in private houses, where the owner insists on his right to injure his own eyes and those of his family.

In a room lit by a lamp only a small fraction of the illumination is direct lamplight. As much as four-fifths may come by diffusion from walls, ceiling and furniture. That is why it is important to have good reflecting surfaces for walls and ceiling. The two extremes are a good white surface, which may reflect four-fifths of the light that falls on it, and a dull black surface which may reflect no more than two per cent. of the light. Light tints come next to white, deep tints come lower down, and dark tints much lower down still. Rooms are sometimes decorated in cream and dull black, and the effect can be very pleasing.

But the black should be in narrow bands, and should cover a small fraction only of the room. Too much black darkens a room and gives a heavy, depressing effect.

Suppressing Light

A red surface looks red because it reflects or diffuses red light only, and absorbs the other colours. A red surface, therefore, is not nearly so good a reflector as white. That is true also of other coloured surfaces: they reflect less light than white surfaces.

A water-colour artist starts with a white sheet, which is just about as bright as it can be. Every time he puts a tint on part of the paper he is suppressing part of the light reflected from it. If he goes on adding tints he will eventually get a dirty, muddy effect, and that is far from being what he aims at. A great part of the art of water-colour painting is to use clear colours and not to cover them up with other colours. The good artist remembers that every stroke of his brush suppresses some light.

Twilight

Twilight is partly explained as an effect of diffusion. When the sun is below the horizon it still illuminates particles of dust and moisture in the air. Some of the scattered light is thrown down to the earth's surface; some of it illuminates particles still higher in the air. Thus we get the diffused glow of twilight for some time after the sun has set. Twilight ends when the sun is 17° or 18° below the horizon. There is a small point of interest here. We can calculate the duration of twilight at any place on the earth's surface at any time of the year by finding how long it takes the sun to sink 17° below the horizon. At the equator the sun sinks vertically at the equinoxes, 15° per hour; so it sinks 17° in 1 hour 8 minutes. And yet, twilight near the equator is commonly said to be a mere ten minutes or so—" at one stride came the dark ". Some sort of explanation seems called for.

Decoration and Reflection

To return to the question of the decoration of rooms, there is a simple way of testing and comparing the reflection from different surfaces. Get a small and rather deep box and cover the inside with good white paper. Cut out a square of small type reading matter to cover the bottom of the box, and place the box in sufficiently good light to enable the type to be read comfortably. Now cover the inside of the box with the material to be tested; there is no need to paste it on. The degree of comfort with which we can now read gives a comparison between the two surfaces. If we use brown paper we shall probably find that the type is unreadable. This is a very useful test when one is choosing a wallpaper or a distemper or paint.

It is sometimes astonishing what a difference can be made with a little light cream paint or distemper. One brilliant day in June I went into an office and found all the electric lights on; even then the lighting was not too good. The reason was not far to seek: the covering of the walls was almost black. Three coats of distemper would have prevented all that waste of electricity. I saw this change actually made in a large room that was to be used as a studio. The change cost ten pounds, and the rent to the next tenant was increased by fifty pounds per annum. I can think of no more profitable investment than light-coloured walls.

An Experiment with Windows

Diffused reflection can be very annoying.

Here is an experiment with windows that are not exactly dirty, but due to be cleaned. We choose a bright day for the experiment, and looking out through an open window we see brilliant contrasts of light and shade. Details stand out vividly; visibility is excellent. We close the window and look through the glass. It is almost as though a mist had come over the landscape. Details that had appeared clear and vivid are slurred or completely hidden; visibility is poor. The reason for the great

difference lies in the thin film of dust on the window. Every particle of dust reflects the sunlight that falls on it, so that a diffused glow is spread over the landscape. Contrast is thus reduced, as though white paint were spread over a picture, and with loss of contrast goes loss of visibility.

On a sunny day I was standing in a room with windows on two sides; the windows needed cleaning. On the side toward the sun there was certainly a bright glow, but visibility was very poor; details of the scene were all but indistinguishable. On the side away from the sun the window seemed quite clear and visibility was good; one had to look closely to see that there was the same fine film of dust on the window. "The sun does show up the dust," says the housewife.

If there are wide-meshed curtains at a window we have little difficulty in seeing through them to the street outside. But they are an effective screen against passers-by. Light is reflected from the netting on the lighted side; it spreads a film of diffused light, just as dust does, and so prevents anyone seeing in from outside. Visibility through the curtain from outside is nil.

Visibility in Aeroplanes

Visibility is of the utmost importance to the pilots of aeroplanes, who have to make decisions in split seconds; and anything that affects the airman's visibility has to be carefully considered. There has to be a screen between airman and the outside world; no one could endure unscreened the super-hurricane in which the aeroplane moves. When the screen comes from the makers it is beautifully clear and the pilot sees a vivid world through it; visibility is as good as it can be. But screens are apt to get scratched. Each scratch may be small and trifling in itself, but the combined effect is not trifling. Diffusion from the scratches spreads a layer of light over the scene the pilot looks at; contrast is reduced, and with it visibility. When he is attacking out of the sun the scratches are hardly seen. But when he is attacking against the

sun, or is himself attacked out of the sun, it is then that the effect is greatest; visibility is lowest just when the need for it is greatest. A transparent surface hard enough to resist scratches is badly needed.

Visibility in Mist

Mist sometimes produces rather odd and unexpected effects on visibility. Light shining on mist creates a curtain of invisibility, just like light shining on dusty windows, so that even a slight mist can hide things a short distance away. Mists do not usually extend upward to any great height, so that when we happen on rare occasions to look up, the mist hardly seems to be there. An airman coming down from above has almost perfect visibility; he may be unaware of the mist till he is safely down at ground level. He suddenly appears, apparently out of the mist, to the amazement of those on the ground.

Sometimes smoke produces reverse conditions. When the air is very still smoke hangs about near the ground instead of being dispersed upwards. Those on the ground may be aware that the day is not specially clear, but that is all; visibility is moderate. To an airman coming down the situation is quite different, especially when the sun is low in the sky. There is a lot of diffused reflection, and a glare that completely hides the ground. Visibility downward is nil, so that the airman has to make a blind landing.

Why our Skies are not Deep Blue

Why are our skies not deep blue like those over the Mediterranean? The answer appears to lie in the smoke of London and Birmingham; other large towns contribute their quotas, but London and Birmingham seem to be the worst offenders. An airman can trace their smoke for hundreds of miles out to sea.

The murk of these cities rises to a height of about ten thousand feet. At that height the airman rises above it and sees it below him. And he sees above him the Mediterranean blue in the sky.

As he rises still higher the blue deepens, until it becomes

almost black. The sky is black at great heights because there is little or nothing to reflect light from it. If there were no light at all reflected from the sky it would look absolutely black.

The Inky Ocean

We find the same kind of thing in mid-ocean, say far out on the Atlantic. Where there is no surface glare the water appears inky black. There are two reasons for this: the water is very deep, and it is extremely pure. There is some reflection from the surface, but any light that enters the water is completely absorbed by it; there are no particles to reflect light back to the eyes. A handful of fine sand thrown into the water will turn a small patch of it bright green, because each particle of sand reflects light back to the eyes. In shallow parts of the sea we often find that the water appears green. The green appearance tells us that there is some kind of fine mud suspended in it, or else that it is so extremely shallow that light reaches our eyes from the bottom.

CHAPTER IX

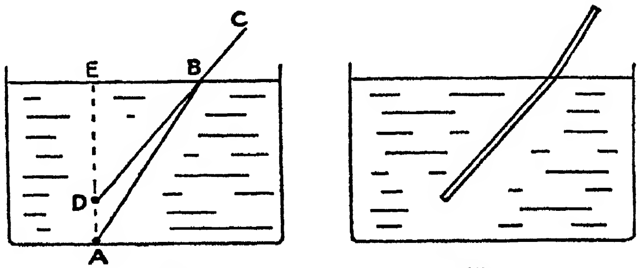
HOW LIGHT IS REFRACTED

(Try to answer these questions first)

Why do we see " a straight staff bent in a pool "?
Why does water appear shallower than it is?
How can we measure the apparent depth of water?
What is meant by " refractive index "?
What is the critical angle?
When do we get total reflection?
Where does a fish see a man on the river bank?
Why can a glass prism be used as a mirror?
Why do diamonds sparkle so brilliantly?
Why can we see the sun when it is below the horizon?
What are the conditions necessary for a mirage?
When is a cold mirage seen?
Why do stars twinkle?
Why can we send wireless messages round the world with straight waves?
How can we draw the refracted part of a ray of light?

" ALL we have power to see," wrote Tennyson, " is a straight staff bent in a pool." But I think we can see a good deal more than that. We can, for example, correct the evidence of our eyes, so that we know the bent appearance is an optical illusion; and we can see why the staff appears to be bent. The staff appears to be bent up where it enters the water, and we can see that that happens because rays of light are bent down towards the surface where they leave the water.

Fig. 73 (*a*) illustrates what observation and reason tell us. It shows a ray of light coming from a dot A at the bottom of a tank and reaching the water surface at B. At B the ray is bent away from the perpendicular, or down towards the water surface. An observer at C sees the dot back along the ray CB; he sees it at D, which is vertically over A. Measurement shows that AD is a quarter of AE which is the depth of the dot. So the lower end of the staff appears to be raised a quarter of its depth. Every



(*a*) (*b*)

Fig. 73.

other point on the staff is also raised a quarter of its depth, and so we get the appearance shown in Fig. 73 (*b*).

The bending or breaking of a ray of light where it leaves one transparent substance to enter another is called ***refraction.***

Coin and Basin Experiment

There is a well-known experiment with a coin and a basin of water which illustrates the apparent raising of an object by refraction. We put the coin at the bottom of an empty basin, and we place the basin so that water can run into it. We stand so that the coin is just hidden from sight by the edge of the basin, and we turn on the water. As the basin fills up the coin appears to rise and it comes into view. When the basin is full and we look down into it we see that the bottom appears to be raised above the surrounding table on which it rests. The

depth of the water appears to be only three-quarters of what it actually is. And that is the same thing as saying that it is a third deeper than it appears to be.

That is true of anything seen through water. Rivers and ponds, indeed, often look deceptively shallow. We should always add one-third when we are estimating the depth of water. A small boy, grabbing at a newt, makes no allowance for refraction, and the newt wriggles away safely below his clutching hand. Men sometimes shoot at

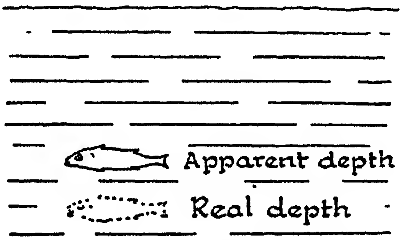


Fig. 74.

fish. If they aim directly at the fish they will almost certainly miss it because they are aiming far too high. To have a chance of hitting the fish they should aim at the spot where the fish actually is, and that is one-third deeper than it appears to be (Fig. 74).

Measuring Apparent Depth

We can measure the apparent rise due to refraction in water, but it would be no use putting a ruler down into the water, for it would itself appear shortened; its inches would look like three-quarter inches, as anyone may see by holding a ruler upright in water. There is, however, a very easy way of making the measurement with fair accuracy. All we need is a sheet of ruled paper, a glass jam jar, and a little water. We cut a circle out of the middle of the paper through which the jar will just slip

(Fig. 75). We trim the circle we have cut out, put it in the jar, and press it down flat on the bottom. We put the remainder of the paper round the jar on the table, and we turn the ruled lines so that they are in line with those inside the jar. We fill the jar with water. The lines below the water seem wider apart than those outside the jar. (They seem wider apart because they appear closer to the eyes.) We raise the outside sheet until the lines once more match; that gives us the apparent depth. We measure the depth of the water, and the depth of the outside sheet below the water surface. We should find that the latter is three-quarters of the former.

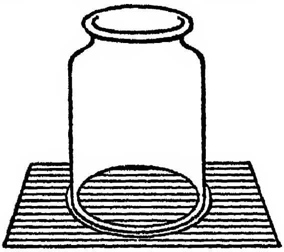


Fig. 75.

Relativity Simplified

Here is a simple little trick for illustrating the effect of refraction on things below water. The trick is as simple as it is surprising. We fill a basin with water and hold a pencil upright in it. We put a thumb at the point where the pencil enters the water, then raise the pencil, keeping the thumb in place. The pencil appears to become much longer, like a telescope opening out, as it leaves the water. And it appears to shut up again as we put it back. If we use a ruler instead of the pencil, it is amusing to see the inch spaces lengthen and shorten as we move the ruler up and down.

Refraction in Glass

Glass is another transparent substance in which it is easy to show the effect of refraction. Any piece of glass will do to show the effect, but plate glass is better than ordinary window glass, and a block of glass is better still. We put a piece of glass on ruled paper and look down at the lines. The parts of the lines seen through the glass seem higher and wider apart than the parts outside the

glass. The effect is even greater than in water, the apparent depth being only two-thirds of the real depth.

Other transparent substances bend light rays, each in its own degree. One of the most extraordinary is diamond. The apparent depth in a diamond is only two-fifths of the real depth. Unfortunately it is not easy to get a large slab of diamond to experiment with.

Seeing a Refracted Ray

We can see the paths of refracted rays in a tank of water. The shadow of one of the sides falls on the water, and the edge of the shadow is then bent down towards the perpendicular. Fig. 76 shows the appearance of a glass tank when the sun is shining on it. When the tank is empty the shadow of one of the sides extends to A; when the tank is full of water it only extends to B. If the shadow is not deep enough for easy observation we can temporarily cover one of the sides with a sheet of cardboard or paper

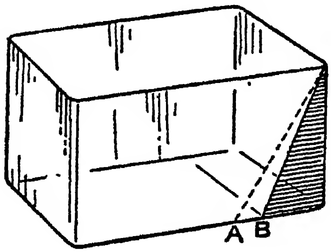


Fig. 76.

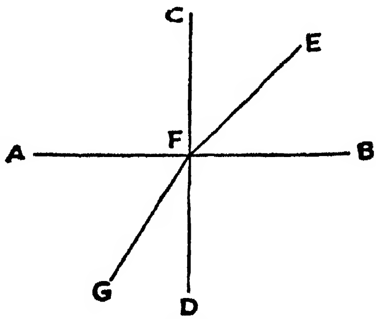


Fig. 77.

What the Refractive Index is

We often use the expression "refractive index" when we refer to the bending of light rays as they pass from one transparent substance to another. Let us see what this expression means. In Fig 77, AB is the surface of a transparent substance with a less dense transparent substance above it, say air over water or glass. CD is a perpendicular, or normal, to this surface. EF is a ray of

light falling on AB, and FG is the refracted ray. Angle CFE is called the *angle of incidence* of the ray (the angle at which the ray *falls* on AB); and angle DFG is called the *angle of refraction.* Notice that both angles are measured from the normal, not from the surface.

Snell, a Dutch mathematician who lived about 1600, thought there must be some law connecting the two angles, and he succeeded in discovering the law. He found that:

$$\frac{\text{sine of angle of incidence}}{\text{sine of angle of refraction}}$$

is always the same for any two transparent substances. This ratio is called the *refractive index* for these two substances. From air to water the ratio is always $\frac{4}{3}$; that is the refractive index. And as rays travel back along the same paths, we can just as well say that the refractive index from water to air is $\frac{3}{4}$.

We usually want the refractive index from air to some other substance. From air to glass it is about $\frac{3}{2}$, and many other substances have refractive indices not greatly different from $1\frac{1}{2}$. One of the most interesting and useful is Canada balsam. It is a sticky kind of turpentine which can be used for cementing glass surfaces. It has the same refractive index as glass, so that it affects light passing through it just as if it were part of the glass surfaces which it joins. So we do not get awkward things happening at the cemented surfaces.

Almost the highest of all refractive indices is that of diamond, which is about $\frac{5}{2}$, or $2\frac{1}{2}$. That is an extraordinary thing about a very extraordinary substance.

There is an easy way of finding the approximate refractive index from air to another transparent substance. We have only to find:

$$\frac{\text{real depth}}{\text{apparent depth}}$$

We have already shown how this method can be used to find the refractive index from air to water, and we can use it equally well with a slab of glass.

A Test of Reasoning

We come now to a very pleasant bit of reasoning. We do the reasoning first, and then we test the result with a simple experiment. Let us think of a ray of light emerging from the denser water into the less dense air. The refractive index is $\frac{3}{4}$, and the ray is bent down toward the water surface, or away from the normal. We take rays farther and farther away from the normal; the refracted rays approach the water surface more and more nearly. Finally we should find a ray that is refracted along the water surface; that is the ray we want to know about.

For all these rays we know that:

$$\frac{\text{sine of angle of incidence}}{\text{sine of angle of refraction}} = \frac{3}{4}$$

When we come to the ray refracted along the surface we know that its angle of refraction is 90°. So:

$$\frac{\text{sine of angle of incidence}}{\sin 90^\circ} = \frac{3}{4}$$

We know that sin 90° is 1; or, if we have forgotten, a table of sines will remind us that it is 1. So the sine of the angle of incidence is $\frac{3}{4}$, or ·75. We look up ·75 in the table of sines and find that it is the sine of an angle of about 48½°. So a ray of light which makes an angle of 48½° with the normal emerges along the surface of the water. 48½° is called the *critical angle* for water.

Let us go a step farther, and suppose we have a ray making an angle greater than 48½° with the normal. It has got beyond the limit of refraction. It looks as if the ray cannot get through the water surface at all. And indeed it cannot. All it can do is to be reflected from the under surface of the water. So it looks as if the under surface should be a mirror for all light that falls on it at a greater angle than 48½° with the normal. Indeed it should be a perfect mirror because it reflects all the light. We should have, as we say, *total internal reflection.*

That is the reasoning. Now for the test.

We fill a tumbler with water and look up through it

from below. We can see rather dimly through the water, as we might expect. We move the eyes to one side and look up at the under-surface of the water (Fig. 78). It has become a bright shining mirror, and we cannot see through the surface at all. It is the best of all mirrors, because it reflects all the light that falls on it and that reaches the eyes. We put a teaspoon in the tumbler and again look up at the under-surface. We see a brilliant reflection of the part of the spoon under water. The part above water cannot be seen through the surface.

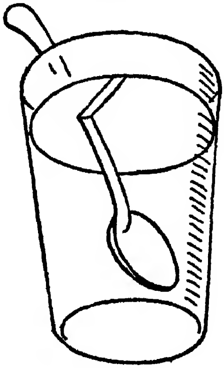


Fig. 78.

It is always interesting to look through, or at, the glass sides of an aquarium. When we look straight through, well, we see straight through. But when we look to one side we get internal reflection, and some of the sides mirror perfectly the animal and vegetable life of the aquarium. We may also notice that everything in the aquarium appears narrower when we look through the side than when we look down from above. A fish turned almost head on to us looks only three-quarters as long as when we view it from above. And everything in the aquarium is magnified because refraction brings things apparently nearer to our eyes.

The Universe of a Fish

Have you ever wondered what a fish sees when it looks up at the outside world? There are those bounding lines at $48\frac{1}{2}°$ to the normal; they form a cone, or funnel, above the fish's eyes (Fig. 79). Within those bounding lines is a cone of rays coming down to the eyes of the fish, and giving it a view of all the space above the water surface. But

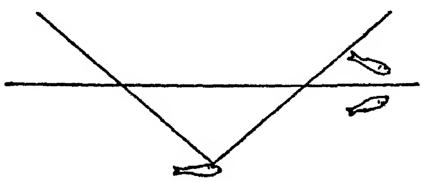


Fig. 79.

nothing is in its right place; everything is distorted by refraction. A fly overhead is too high up. An angler on the bank appears squat and leaning forward. The view of the whole outside world is concentrated into a funnel. Overhead there is little distortion, but near the horizon the compression becomes more and more excessive. Beyond its illuminated funnel, if a fish can see so far, the under-surface is a mirror that reflects the underwater life. A very odd environment, which human beings can see only vaguely for a few seconds when they turn on their backs and open their eyes under water. Even for a few seconds the vision is very imperfect. Our eyes are adapted to seeing in the air, where light is refracted from the air to the transparent membranes of the eye. They are not adapted to seeing under water, where the refraction is quite different, from water to the eye membranes.

Try to imagine that men had been water animals, unable to leave the water and venture into the air, and that we had eyes adapted to seeing under water. What odd ideas we should have of the world outside our watery environment! Could we reason back from the funnel that contained our view of the outside world, to the flat water surface? Or would our eyes forever deceive us?

A Glass Prism as a Mirror

You may have observed that the sine of the critical angle for any transparent substance is equal to the refractive index from that substance to air. That is of course because the sine in the denominator is sin 90°, which is one. The refractive index from glass to air is $\frac{2}{3}$, so the critical angle of glass is the angle whose sine is $\frac{2}{3}$, or ·667. We look up ·667 in the table of sines, and we find that this is the sine of an angle a little less than 42°. It is fortunate that the critical angle of glass should be less than 45°, because this gives us

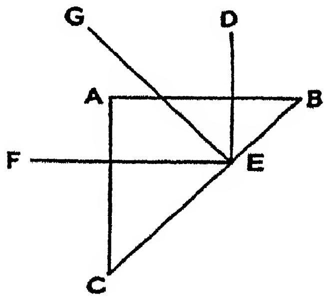


Fig. 80.

a simple method of using a glass prism as a mirror. In Fig. 80, ABC is a glass prism with two of its angles 45°. The prism is placed so that the light we want to reflect falls on one of the short sides, AB, at right angles. Rays of light in the direction DE, at right angles to AB, fall on BC at an angle of 45° to the normal (GE). This is greater than the critical angle which we know to be 42°, so the rays are totally reflected by BC. The ray DE is reflected along EF, for example. Glass prisms are used as mirrors in many optical instruments because of the excellent reflections they give.

The Submarine Periscope

The periscopes of a submarine rise about thirty feet above the hull, so that the submarine can remain submerged whilst observations are being made of the sea and the sky. Prisms are placed at the upper and lower ends to reflect light down to the eyes of the observer. The

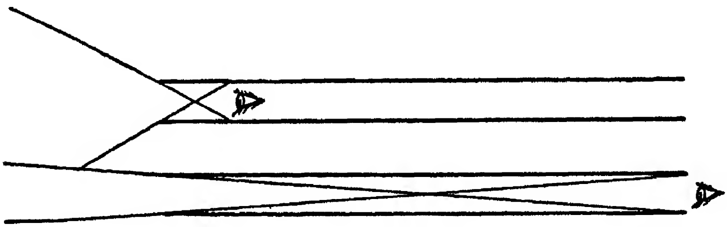


Fig. 81.

upper prism can be rotated, because it is very necessary to keep a watchful eye on the sky. Now, if you imagine your eyes at the end of a tube four inches wide and thirty or forty feet long, you will see that you are going to have a very narrow range of vision, whereas if the eyes are close up to the outer opening the range will be wide. The difference is illustrated in Fig. 81. We want of course the widest possible range of vision, so a series of lenses is introduced between the two prisms. The lenses are arranged to produce an image of the eyes just behind the upper opening. The eyes see the outside scene as if they

were in the position of the image. It is not advisable to have too many lenses because each of them cuts off a small part of the light, and so reduces visibility.

The upper prism of the periscope is diamond-shaped, so that it can be used to reflect light at various angles, including light from overhead.

The Beauty of a Diamond

We expect a lot from a thing so expensive as a diamond, and we get quite a lot, though probably nothing commensurate with the value set on it. The great attraction of diamond is its small critical angle; that and its hardness. The critical angle is the angle whose sine is $\frac{2}{5}$, or ·4; and that is less than 24°. Light can easily get into a diamond through any of the facets cut and polished round it; to get out again it has to strike one of the facets at an angle of less than 24° with the normal. In Fig. 82 rays of light in the angle AOB are totally reflected at O. Only rays in the cone of which BOC is a section can escape at O. The other rays are reflected to other facets, and probably again and again reflected. Once it gets in, it is not too easy for light to escape from a diamond. When it does escape we get the brilliant flashes of accumulated light for which the diamond is famous, and that give it its high value as a jewel. Glass imitations of diamonds do their best to imitate their brilliance, and indeed they can be made to sparkle so that anyone might be deceived into thinking they were the real thing. But they do not stand long and loving scrutiny, and doubts begin to arise. Glass does not take the high polish of the diamond, and a critical angle of 42° is a poor substitute for 24°.

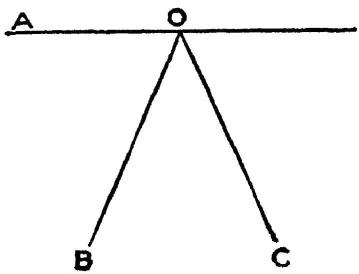


Fig. 82.

Refraction in Air

There is of course a big difference in density between air and water, and between air and glass. But these big differences are not necessary for refraction to take place. We can still have refraction with very small differences of density. For example, the density of the atmosphere gets less and less as we ascend, and so we have the conditions for refraction. A ray of light coming down from above passes through denser and denser air, and so it is more and more bent down towards the vertical. The bending is not great, but it has effects that affect measurements. Fig. 83 shows the light of a star curving down through the atmosphere; the curve is greatly exaggerated. An observer at O sees the star back along the final direction of the ray, that is, in the direction OA; whereas we know the star to be in the direction of the dotted line OB. The star appears higher in the sky than it actually is.

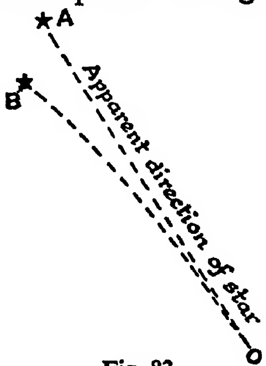


Fig. 83.

The rays of the setting sun pass through a great extent of atmosphere before they reach our eyes. They travel through air that becomes progressively denser, and so they are refracted more and more. We see the sun, as we see a star, higher than it actually is. Indeed the sun is completely below the horizon before we begin to see it set. We see it above the horizon in the morning whilst it is still below. "The best of all ways to lengthen our days," wrote Tom Moore, "is to steal a few hours from the night." And that is exactly what refraction does for us.

Normally the density of the atmosphere decreases as we ascend; but that is not always the case. We may have a surface strongly heated by the sun. Dry sand, for example, absorbs heat from the sun and retains most of it close to the surface. The air just above the heated surface becomes strongly heated also, and so it is less

dense than air just above it. We have an inversion of the usual arrangement of densities. Rays of light near the surface of the ground are in the region of the inversion. Refraction curves the rays, not up, but down (Fig. 84). Some of these rays may strike a layer of less dense air at the critical angle, and so they may be reflected up to the eyes of an observer. The observer sees objects down along the final, reflected, rays, and so he sees them as if they were their own reflection in the sand.

The Hot Mirage

That is what happens when there is a mirage in a highly heated desert. The heated sand heats the air above it, and so we get an inversion of the density gradient: low density along the heated surface, higher density in the cooler air above. Light rays are turned down, and then

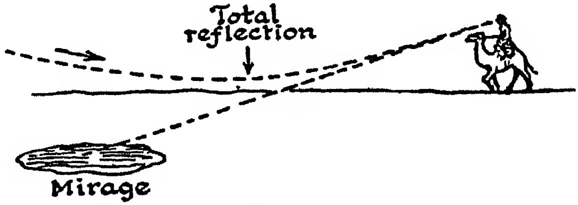


Fig. 84.

up, so that the scorched and weary traveller sees an image of the sky, and the image looks like a pool of cool water on the face of the desert. He does a little wishful thinking; he imagines that he actually does see a pleasant pool with palm trees growing about it. He hurries towards the imagined water, and as he advances, so the mocking mirage recedes. Perhaps it vanishes and the desert lies empty before him. That is the explanation of the mirage of the hot desert: partly it is the physical facts of refraction and total reflection, and partly imagination stung into abnormal activity by excessive heat and drought.

Mirages at Home

But we do not need to visit the Sahara in order to see a mirage: the phenomenon is common enough in our

own country, though we often fail to notice it because we are not so tragically concerned as is the desert traveller. We want the same conditions as in the desert: a long, level stretch, and a very hot day. On such a day a long stretch of asphalt or concrete road gives the necessary conditions; it has a long. heated surface which heats the air immediately above it, and so reduces its density. We are much more likely to see the mirage if we bend down. Our eyes then receive rays of light almost grazing the road surface, and it requires only a small bend in the rays to produce the effect. Cyclists often see mirages on hot days just before they reach the top of a hill with a long straight road in front of them. For a moment they are looking along the downward slope almost at ground level. They see, or imagine they see, pools of water on the distant roadway. The illusion vanishes when they actually reach the top and are high above the road surface.

We sometimes get the mirage effect when a long straight wall is strongly heated, like a piece of the desert set up on end. The air near the heated wall is much hotter than air a few inches away from it, so that there is an increase in density as we move away from the wall. Light almost grazing the wall is refracted and reflected like light along the hot surface of the desert. If we turn Fig. 84 on its side, it will serve quite well to explain the mirage sometimes seen along a hot wall. To see this mirage we have to stand close to the wall, and look along it.

The Cold Mirage

Cold mirages are not nearly so common as hot ones, but they do sometimes occur over very cold ground or water. The usual arrangement of less dense air over more dense results in raising the apparent positions of distant objects, as we have seen in the case of the heavenly bodies. We do not get a mirage because the rays of light are not reflected. Only when the air near the ground is extremely cold, much colder than the air just above it, do we get a sufficient difference in density to produce a mirage. In these conditions light rays may be reflected downward, as they are from the under-surface of water.

Rays of light which started upward at a small angle from a distant object reach the eyes of an observer in a downward direction (Fig. 85). He sees the object back along

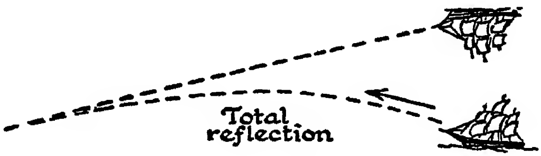


Fig. 85.

those rays, as an inverted image in the sky. The cold mirage is most often seen over water. Ships have been seen upside down in the air when they were actually below the horizon.

"The Quivering Heat"

Sometimes on a hot day we see the air quivering over asphalt or a tarred roof, or some other surface that easily becomes hot. These are the conditions in which we get small upward air currents: a strongly heated surface with hot air over it, surrounded by cooler air. The density of the air above the hot surface is continually changing with the interchange of hot and cooler air. The changes may be only slight, but they are sufficient to produce changes in refraction; so that light rays continually change their directions, and we get the quivering effect.

The Twinkling Stars

We look at the stars and see them twinkle, and sometimes wonder why. The reason is that a star is a mere point of light; even when it is looked at through a powerful telescope it appears to have no width. We have to think of a single ray of light from a star passing through an atmosphere whose density at every point is continually undergoing small changes. Each change in density means a change in refraction. The changes are small, but they are sufficient to break the continuity of the light ray, and so to produce the effect of twinkling. We even get colour

changes, as one colour comes through in one twinkle and another colour in another.

As we should expect, the twinkling is greatest when the star is near the horizon; overhead stars hardly twinkle at all. When a star is near the horizon the ray of light from it has to pass through a great extent of atmosphere before it reaches our eyes, and there is ample room for changes in refraction. Planets hardly twinkle at all. Every planet has a small perceptible disk. Changing refraction may rob us for a moment of the sight of one part of the disk, yet the rest of it remains, and so we do not get twinkling.

Twinkles Spread Out

We can use a mirror to spread out the light of a star, and so to persuade it to exhibit its twinkling more clearly. We choose a bright frosty night for the experiment when the stars are twinkling strongly in an otherwise dark sky. And we choose a bright star low down in the sky. Sirius is perhaps the best for this purpose. It is a winter star, low down in the sky, and the brightest of all the fixed stars. It is easy to find because the Belt of Orion points down to it. We turn towards Sirius, and hold a small hand-mirror so that we can see the star reflected in it. We move the mirror rapidly to and fro, and we see the light of Sirius spread out into a narrow closed curve. We see a bright star at each end of the curve; that is because the mirror comes to rest for an instant before it begins to move back in the opposite direction. Between the two bright ends we should be able to see the twinkles spread out. We change the speed of the mirror till we get the clearest result. We should be able to see spots of bright light where the bright twinkles come, joined by narrow bands of dull light where the light has been refracted away from our eyes.

Refraction of Wireless Waves

We have seen how temperature changes the refractive index of air by changing its density. Humidity also changes refraction: damp air has a higher refractive

index than dry air. This effect has been observed with waves much longer than visible light waves; it is indeed most observable with wireless waves about four inches long. Changes in the amount of moisture in the air can play odd tricks with short wireless waves.

In the early days of wireless communication, critics pointed out that wireless waves are electromagnetic, and that they travel in straight lines like visible light waves. It would be impossible to communicate by them except over very short distances, because the waves would go straight out, and would not follow the curvature of the earth. So said the critics. The explorers went ahead with their experiments; Marconi successfully flashed signals between Cornwall and Newfoundland. Yet the critics were right, up to a point. That point is sixty-five miles above the earth's surface, where the Heaviside layer begins. It is a region of ionised, or electrified, air. Ionisation has a remarkable effect in refracting wireless waves longer than four inches. These waves are continually refracted and reflected downward, so that they follow the curvature of the earth without leaving the atmosphere. Ionisation of the upper air makes possible wireless communication over long distances. It realises, literally, the idea that light waves can travel seven and a half times round the world in a second. And it seems to knock on the head an early idea that wireless waves might be used to send messages to Mars. I say "seems" because so many miracles have come to pass that it is unsafe to make a negative prediction.

How to draw Refracted Rays

It is useful to be able to draw a refracted ray, and there is an easy way of doing it. In Fig. 86 AB is a ray of light falling on a water surface at B. We want to draw the refracted ray. With centre B we draw a circle with radius AB. We draw AC at right angles to BC, and we divide BC into 4 equal parts. We measure BD equal to 3 of these parts. We draw DE at right angles to BC to meet the circle at E; E is on the circle. We join BE, and BE is the refracted ray. To find the refracted ray of EB

(from water to air) we reverse the construction: divide BD into 3 equal parts, and make BC equal to 4 of these parts.

For air and glass we divide BC into 3 equal parts, and make BD equal to 2 of these parts. For air and diamond we divide BC into 5 equal parts, and make BD equal to 2 of these parts.

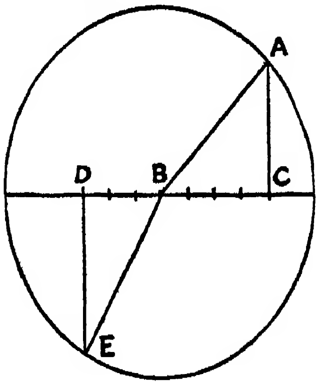


Fig. 86.

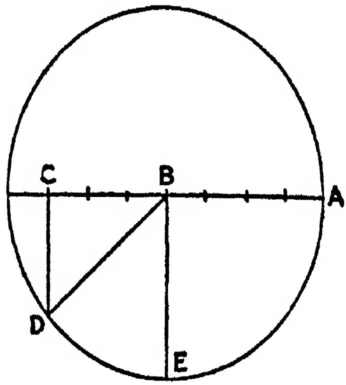


Fig. 87.

We can also construct the critical angle (Fig. 87). AB is a ray along the surface of water. To find the refracted ray we divide AB into 4 equal parts. We make BC equal to 3 of these parts, and draw CD at right angles to AC; D is on the circle. BE is the normal at B. We join BD, and angle DBE is the critical angle.

For air and glass we divide AB into 3 equal parts, and make BC equal to 2 of them. For air and diamond we divide AB into 5 equal parts, and make BC equal to 2 of them.

CHAPTER X

OPTICAL ILLUSIONS

(Try to answer these questions first)

What is an optical illusion?
Why does a mirror usually not give top to bottom inversion?
What is the chi-phenomenon?
What are the " canals " of Mars?
How are newspaper pictures made up?
How can we see spherical drops of rain? How do we usually see rain?
What is the " railings illusion "?
What is meant by " scanning " in television?
How does the body feel accelerations?
What is the egocentric illusion?
Why do fields seem to swing round on a railway journey?
How can lines be used to change one's apparent height or width?
Why do the sun and moon look larger when near the horizon?
How did Greek architects curve the lines of their temples?
Why does a searchlight beam sometimes look curved?
What is the relief illusion?
Why do slopes often look steeper than they are?
What is irradiation?

WE live in a world of optical illusions; indeed our whole knowledge of the world may be regarded as an illusion.

Some of the illusions are so familiar that we have almost stopped regarding them as illusions. We see our own image in a mirror, and we take the illusion for granted; we interpret it without conscious effort. We see a walking-stick in water, apparently bent; we probably class the phenomenon as an illusion, because it is not quite so familiar as reflection; the interpretation does require a small conscious effort. We see a mirage, and we have no doubt that it is an illusion; we count it as an illusion even after we have analysed it, and decided that it is a result of refraction and total reflection. Probably we classify a phenomenon as an illusion when we have consciously to interpret it as something different from what it appears to be.

The Mirror Illusion

There is one point about the mirror illusion that often worries people. "How is it," they ask, "that we see the mirror image inverted left to right, but not top to bottom?" The answer is that we usually see ourselves in upright mirrors. The most obvious inversion is back to front; *that* we hardly notice. We swallow the camel, and then strain at the gnat of right to left inversion. We are so conscious of ourselves, of our little peculiarities, and of our little departures from exact symmetry about a vertical line. We turn sideways to the mirror. There appears to be no inversion between back and front of the body. But suppose we were nearly symmetrical from back to front of the body, and suppose we call the back, left, and the front, right. Then we get the same right and left inversion as before. "Back" and "front" are absolute terms; "left" and "right" are relative. Our own bodies are the standard for the relative terms, and we have to beware of confusion between the standard and things to which it is applied.

If we want top to bottom inversion by a mirror we have to place the mirror in the appropriate place. We place the mirror horizontally over the head, or we stand on it.

Fig. 88 shows three reflections, without the confusion introduced by the intrusion of the bodily left to right standard, except as a standard. (*a*) Shows top to bottom

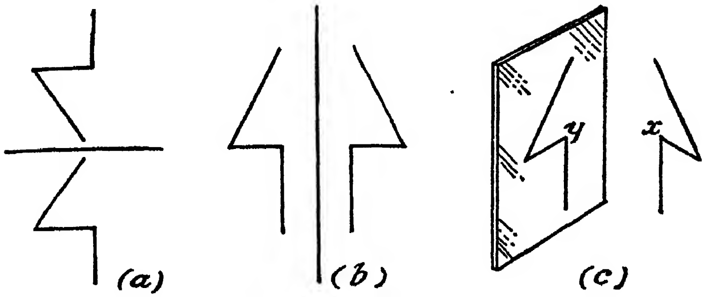


Fig. 88.

inversion; (*b*) shows back to front inversion; (*c*) attempts the difficult task of showing left to right inversion. We have to imagine our eyes between object and image; the point marked *x* is on the right of the object (your right), its image, *y*, is on the right of the mirror image (your right).

Illusion at the Pictures

Sometimes we deliberately create illusions, and accept them placidly for what they appear to be. We go to the cinema; we see people and objects move on the screen; and we accept the fact that they are moving, even though we know very well that the whole thing is an illusion. What actually happens is that the projector throws on the screen one still picture after another; so far as the actual projection is concerned there is no movement on the screen; the movement is an illusion. The shutter in front of the projector helps the illusion; it cuts off the light whilst one picture is being moved out of the way and the next picture moved into place. The illusion depends finally on eyes and brain. The eyes see one still picture after another, and the brain runs the pictures

together, so as to give the illusion of movement. That is the illusion we contentedly accept.

The illusion of movement on the screen is due in the first place to the *chi-phenomenon*—the running together of disconnected objects to give a sense of continuity; and, in the second, to *persistence of vision*—anything seen by the eyes does not vanish instantaneously; it is retained for about a tenth of a second. When still pictures are presented in quick succession to the eyes we see at least two at once: the picture just brought into view, and the fading image of the previous picture. The eyes and brain bridge the gaps. When the speed is slowed down the moving picture begins to flicker; when the speed gets below ten pictures a second we begin to see them as separate pictures. We can no longer bridge the gaps, and the illusion of continuity is destroyed.

Dots and Lines

We turn up the picture page in a newspaper and look with varying interest at the pictures. We are usually unaware that the picture we see is an illusion. We look at part of the picture through a magnifying glass, and the illusion is destroyed. What we took for part of a picture turns out to be a number of dots arranged in various patterns. The more powerful the magnifying glass, the more completely is the illusion destroyed by the separation of the dots. Without the glass, the eyes run the dots together to give the illusion of continuity which turns the dots into a picture.

When disconnected objects are comparatively big we are more likely to get the illusion of continuity if they are at a distance. A famous illusion of this kind is the "canals" of Mars. They were seen as channels (*canale*) by an Italian astronomer, Schiaparelli; the word was translated into English as "canals", and the canals were instantly filled with water in the popular estimation. The logic was irresistible: canals, intelligent creatures to construct them, hence a highly developed life on Mars. And writers prone to decry human intelligence raised the

Martians to a high level of intellect. But there seems to be little doubt that the lines on Mars are an illusion. The eyes run together various small markings and so produce the illusion of lines.

Persistent Vision

We hold a glowing match or stick in the dark, and swing it round at arm's length. If we can manage a speed of ten revolutions per second, the glowing end begins a new revolution before the appearance of the last has quite faded, and so we have the illusion of a complete circle of red light. When we slow the speed down we see a whirling arc of red light. The arc is brightest at the point where the glow actually is, and it tails off down to the point where vision has faded completely before the whirling light comes round again.

For the same reason we see falling rain, not as spherical drops, but as long streaks. If, when the sun shines on rain, we look up in the direction away from the sun, we see flashes of light where drops reflect the sunlight. The flashes of light appear drawn out into lines in the direction of the rain by persistence of vision.

There is a way of undoing this effect. We look at a group of raindrops high up, and we follow them down with the eyes. So long as our eyes follow them down we see the drops as separate spheres.

Sometimes an airman has this done for him when he does a stall turn in the rain. For a short time he is falling at the same rate as the raindrops, and the drops appear to stand still as little spheres. Then he begins to descend rapidly, and the drops appear to rush upward in lines slanting back from the nose of the 'plane.

Persistence on Railway Embankments

When we are in a rapidly moving railway carriage we find it difficult to see the shapes of objects near the train; details on the objects appear to be drawn out into lines. It is the same illusion as the raindrop lines, another effect of persistent vision. We can resolve the illusion in

the same way. We fix our eyes on a point as far ahead as possible; then we follow the object round with our eyes. The object we look at seems to come momentarily to rest, and we see the details of it clearly. So far as our eyes are concerned, we have moved with the object, and so it has been at rest to our eyes.

The Railings Illusion

When we stand near closely set railings, the scene behind them is all but invisible; we may get glimpses through the narrow spaces between the railings, but not enough to give us a picture of the scene. We begin to walk along rapidly, looking through the railings, and at once we see the whole scene in a subdued light. It is an illusion. Fig. 89 shows what happens at one of the gaps between the railings. The point A is seen through the gap when the eye is at X, the point B when the eye is at Y, and the point C at Z. In the time it takes to walk from X to Z, the eyes scan the scene from A to C. And the same sort of thing is happening at all the other gaps through which the eyes can see. The eyes see all parts of the scene, one part after another in rapid succession; they hold each part long enough for the rest to be seen before it has faded, and so we have all the parts fitted together into a complete picture. The subdued light is due to the fact that most of the light that comes towards the eyes from the scene is stopped by the railings.

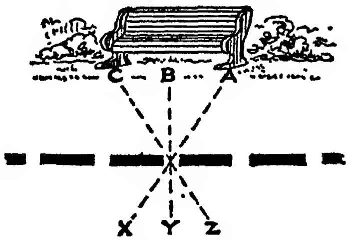


Fig. 89.

We get the illusion of television in a somewhat similar way. A narrow beam of light "scans" the screen; it moves across the top of the screen, jerks back and scans the next line below, and so on till the whole screen has been covered; then the beam of light jerks back to the top of the screen, and begins to scan it once more. There may be more than 400 scanning lines, and the whole

screen has to be scanned at least sixteen times in a second. Only a very small fraction of the screen is illuminated at once, but the screen retains the illumination for a fraction of a second, and so do the eyes. Thus we get the illusion of a completely illuminated screen. The scanning beam contains all the variations of light and shade in the original scene, and the eyes run successive pictures together to give the illusion of movement.

Illusions of Movement

There are many illusions connected with movement. Unless we are continually reminded of it we are very seldom conscious of our own movements. Perfectly smooth movements we are not conscious of at all; we can only establish their existence by reasoning. Sight is not decisive, because our eyes are easily deceived. But our bodies are very sensitive to accelerations; we perceive them as variations of weight. An airman, doing a rapid turn, may suddenly find himself six times as heavy as usual, and he has no doubt about his extremely rapid acceleration towards the centre of the curve in which he turns.

A rapidly moving train continually reminds us of its movement. Small jerks produce sudden accelerations in this direction and that; the slightest curve produces an acceleration toward its centre; and every change of speed has its effect on the bodies of the passengers. In a smoothly running train we may hardly know whether we are moving or not; and there are numerous smooth movements of which we have no consciousness whatever. In the latitude of England the earth is rotating at a speed of about 600 miles per hour; no one is aware of the slightest movement. The earth revolves round the sun at a speed of about 18 miles per second, and no one feels the movement. We all see the daily illusion of sun, moon and stars circling across the sky. Only by reasoning do we perceive that the apparent movements are illusions, and so we arrive at the real movements. Oddly enough, very few people notice the one real celestial movement that is readily observed: the movement of

the moon from right to left as it circles round the earth. This movement may be perceived by noting, night after night, the moon's position amongst the stars; or even more simply by noting that it rises about three-quarters of an hour later each night.

The Egocentric Illusion

We are apt to regard absence of movement as the normal thing, and still more apt to regard ourselves as the normal. We relate movements to ourselves, and usually to ourselves at rest. That is the egocentric illusion: the illusion that "we are the people".

But when we expect to start moving we can just as easily regard our own movement as the normal, and so we see other things as if they were at rest. We are sitting in a train which has drawn up at a station, and we expect to start off again at any moment. We look out at another train which has drawn up beside us, and sure enough we begin to slide smoothly past it. That is the illusion. Then we appear to reach the end of the other train, and the opposite platform comes into view. The illusion ends abruptly. We pull ourselves up, and find that it was the other train moving all the time. We expected to start moving, and so we thought we were moving. With an effort of the will we can deceive ourselves into thinking that either one train or the other is moving. We can create our own illusions.

Illusions of Parallax

On a railway journey it requires very little effort to feel that we are more or less motionless, and that the near landscape is rushing past us. It requires no effort to see that the distant landscape is continually swinging round in the direction in which we are going. The farther off an object is, the quicker it seems to move. We fix on a spot in the middle distance, and hold it still by following it with our eyes. Then the rest of the landscape seems to circle round the fixed spot. The part beyond appears to move with the train, and the nearer part against it.

These illusions are effects of parallax. As we move along, farther objects seem to move with the eyes past nearer objects. In Fig. 90 an observer at D sees objects A, B, C, one behind another. When he has moved the distance DE, he sees them in the directions EA, EB, EC. That is, he sees B to the left of C, and A to the left of B. If he has followed the object at B with his eyes, then A appears to have moved to the left, and C to the right.

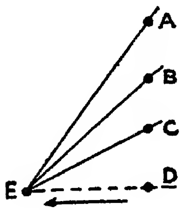


Fig. 90.

We sometimes have the illusion that the moon keeps pace with us as we walk along a street. This is another example of the parallax illusion: the far-distant moon appears to move with us past all nearer objects. The moon is so far off

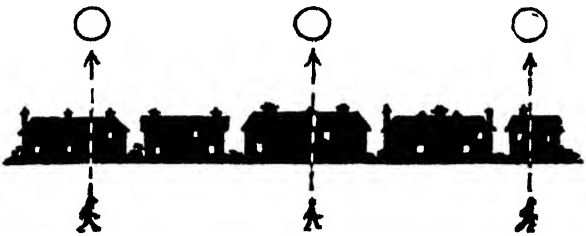


Fig. 91.

that all lines drawn to it are parallel. If the moon is due south, for example, it is equally due south from any point where we happen to be. So we get the effect shown in Fig. 91.

Confused Parallels

Fig. 92 illustrates an odd illusion about the direction of lines. Look across the picture from one corner. The long lines appear to get closer together or wider apart. Actually they are exactly parallel. The short oblique lines do not look as if they would join across, though they are parts of the same lines. The double illusion is probably due to errors of judgment. The oblique lines

introduce a confusing circumstance when we try to judge whether the long lines are parallel; and the long lines similarly confuse us about the oblique lines. With either set of lines separately we have no difficulty in judging correctly. This illusion can be controlled. With an effort of the will we can see the lines as they actually are, especially after we have convinced ourselves by measuring that they actually are parallel.

We can repeat the illusion as a dinner-table trick with the help of a few matches. We set out three matches in a straight line. We remove

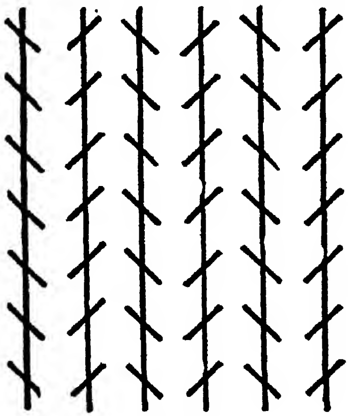


Fig. 92.

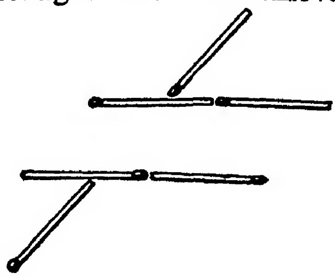


Fig. 93.

the middle match from the line. Then we put two or three matches across the inner ends of each match, so as to have two parallel lines crossing them obliquely (Fig. 93). It is almost impossible to judge that the two matches are parts of a straight line, unless we actually look along them. We can convince any doubters by replacing the match that had been removed.

Illusions with Lines

Sometimes we use lines to create illusions of height or width. When we want to add a cubit to our apparent stature we take thought, and wear clothes with vertical stripes. The effect is to make us look taller and slimmer. If we are altogether too slim we wear horizontal stripes, and so increase our apparent width. Fig. 94 shows a

lady and her fiancé. On Saturday she wore a costume with vertical stripes, and felt comfortably tall and slim. Unfortunately her fiance wore horizontal stripes. On Sunday each decided to please the other by changing over to the other's stripes: they were very much in love. After the second unfortunate encounter they decided that team work was a desideratum.

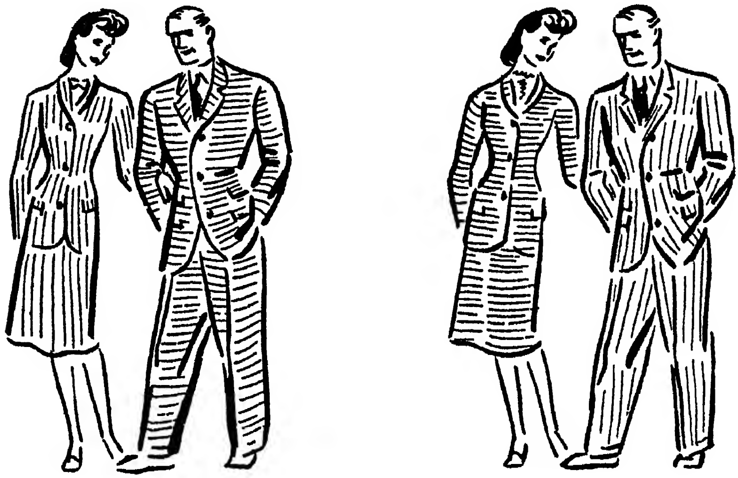


Fig. 94.

Rugger forwards are usually so tall that they do not need to accentuate their height, so they often wear jerseys with horizontal stripes. Thus they add an appearance of width to their height, and so acquire that intimidating appearance for which rugger forwards are notorious.

An Illusion of Isolation

It is difficult to estimate the size of an object isolated in space, because there are no other objects to relate it to. We see a man or a cow in the distance, and we have got a standard by which we can measure other objects, and estimate their distances. But a completely

isolated object might be any size. " At times the small black fly upon the pane, may seem the black ox of the distant plain."

A submarine sights a warship. It has no range-finder, so it has to estimate the range by its apparent size. To do this it must know the real size, and there lies the difficulty. A light cruiser may have very much the same silhouette as a battleship. If the submarine guesses wrongly, its estimate will be miles out. If it mistakes a light cruiser for a battleship its estimate will be far too great; if it mistakes a battleship for a light cruiser its

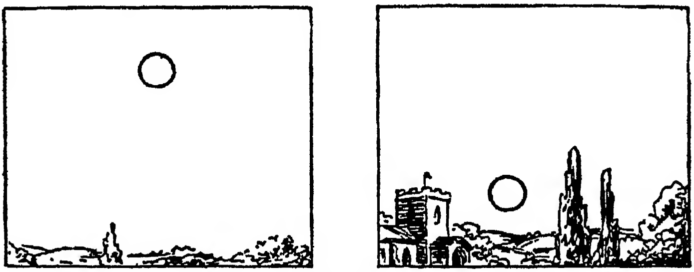


Fig. 95.

estimate will be far too small. A heavy cruiser with the same silhouette would add a further complication. All very confusing for the submarine commander.

There is no doubt, however, that an isolated object looks smaller than the same object when it is surrounded by other things; it seems to shrink into itself. This was one of the earliest optical fallacies to be recognised. The Greeks had numerous columns round their temples. Most of the columns were seen against the temple walls as a background; but the columns at the corners were seen against the clear sky; consequently the corner columns looked a little smaller than the others. To compensate for this the corner columns were made a little wider than the others, and so the optical effect of equal size was attained.

The sun and moon look bigger when they are near the horizon than when they are high up in a clear sky.

(This is apart from the effect of haze on the horizon, which has the added effect of blurring outlines.) Everyone has noticed this phenomenon repeatedly, and there has been much discussion about it. The angular width of the sun has been measured in both positions, against a clear sky and a clear horizon, and there is no difference; so that the appearance is definitely an illusion. The best explanation appears to be that high up in the sky the sun is isolated, whereas near the horizon it is seen surrounded by, or close to, other objects (Fig. 95).

An Illusion of Distance

Fig. 96 illustrates an illusion which is allied to the last; it is a common fallacy in the estimation of distances. The distance from A to B appears to be greater than the distance from B to C, and yet the two distances are equal. The dots between A and B help us to judge the distance, but there is nothing between B and C to aid the judgment; we underestimate the distance of the isolated

Fig. 96.

spot. The difficulty is commonly observed of judging distances on an almost empty sea. The presence of ships here and there, with their varied apparent sizes, is a considerable help in this connection. But it is still a difficult problem for people unacquainted with the sea, and accustomed only to crowded landscapes.

Another example of the same illusion may be seen when a patch of rough ground is enclosed in order to make a garden. The almost empty plot of ground looks smaller than it actually is; but every addition of paths and flower beds increases the apparent size, especially when the changes involve differences of level.

Straight Lines Curved

We have all learnt that " no power on earth, however great, can draw a string, however fine, into a horizontal

line that shall be absolutely straight". In less poetical language, telegraph wires sag in the middle. On railway journeys we see the wires go up and down: up when we pass a telegraph pole and down towards the middle. There is an optical illusion which is very much like this: long horizontal lines, especially lines in buildings, appear to sag slightly in the middle. Greek architects knew about this illusion, and took steps to counteract it. The Parthenon at Athens is usually counted the most beautiful of all Greek buildings; its lines are curved so as to give the illusion of straight lines. The floor beneath the columns has a slight upward curve of 2·6 inches in a width of 100 feet. The architrave above the columns has an upward curve which is a very little more. The effect of these slight upward curves is to undo the illusion of sagging, and so to give the illusion of straight horizontal lines The sides of the Parthenon are more than twice as long as the front, and the upward curves are correspondingly greater, 4·4 inches. Fig. 97 shows the curves greatly exaggerated so as to make them visible. The columns also are curved, to undo another optical illusion. Columns which are the same width all the way up look slightly waisted, so there is a slight outward bulge to undo this effect. The columns

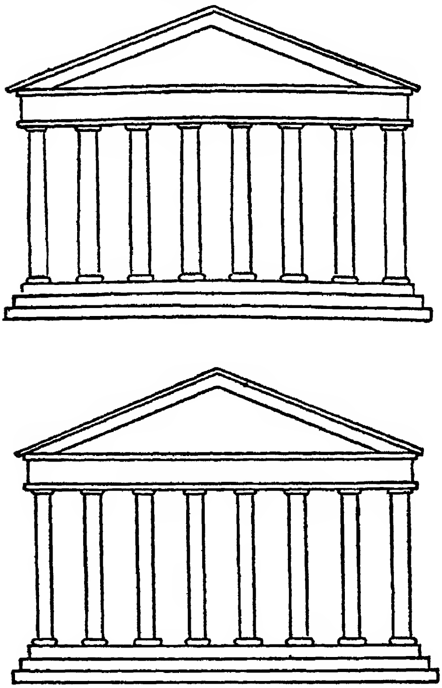


Fig. 97.

are 34 feet high; the outward bulge is three-quarters of an inch.

There is an inferior method of overcoming the sagging illusion which is commonly used by architects who do not wish to take the extreme pains taken by the Greeks. Long straight lines are broken by having a part near the middle project outward, as in Fig. 98. When the building is looked at from ground level, the middle part appears raised above the ends, and so the sagging illusion is undone.

Fig. 98.

Curved Searchlight Beams

I have been asked by a good many people why it is that horizontal searchlight beams go down and then up. It has even been suggested that we have got a new kind of beam. The answers are that they don't, and we haven't. Searchlight beams go straight out like other beams of light; that is obvious enough to searchlight operators, who look out along the beams. The down-and-up appearance is an illusion; we get it when we are not too far from the beam, and somewhere near the visible part of it. It is the sagging illusion that we see in long horizontal lines of buildings. Some good observers see the beam as a flat parabola, with its vertex downward and at the part of the beam nearest to them.

Where Perspective Fails

We are subject to so many optical illusions that geometrical perspective does not give a true representation of what we see. It does not give the optical sag in long horizontal lines that is seen in buildings and searchlight beams.

We habitually overestimate heights. I have a too tall pear tree in the garden; it is 25 feet high by measurement. Many people have made an estimate of its height; so far the lowest estimate is 30 feet, and that was made by a man who knew he had to allow for the overestima-

tion of heights. Geometrical perspective does not represent this overestimation.

There is at least one other way in which perspective fails to represent reality as we see it. Our range of distinct vision is quite narrow, only about 10°. If we hold the two hands upright and at arm's length, they give us just about the range of distinct vision. To test this, look steadily towards the line where the hands meet, but focus on the background. There is no distinct vision of the background on either side of the hands. We look at a wide building and we see only a part of it distinctly at any one time. But our eyes flick to and fro, from one centre of vision to another, and so we build up a composite picture of the building. This picture is not the perspective picture. When we see an architect's perspective we are inclined to say, " Oh, it looks like that, does it?" The perspective is hardly what we had expected after having seen the building itself. The eye picture is probably composed of many changing perspective views joined into a rather vague whole, and smoothed over by the unifying effect of optical illusion.

The Camera also fails

The camera does not help much in presenting wide views as we see them, even apart from the lack of depth in ordinary photographs. The camera has not the power of reproducing our illusions, though photographers have made valiant efforts to induce it to do so. A friend took photographs of a wide Italian building by swinging his camera round so as to photograph it in sections. He was imitating, as he thought, the action of his own eyes that flitted from point to point over the building. But when he fitted the sections together he found that he had got a photograph of a building that swung round in a great curve; it bore little resemblance to the building his roving eyes had pictured.

The camera can do a lot better than that. The experienced cameraman can change the position of his lens, or of his camera for that matter, so as to get a composite picture that is something like the architect's perspective.

But it is still not the flitting eye picture. Only a skilful artist can get anywhere near an impression of what we see.

We can sometimes go so far back from a wide building that the illusory effects begin to fade out. The stereoscopic effect, due to binocular vision, almost disappears, and we see a flat picture. The downward sag of straight lines is straightened out. We see the whole building in a single perspective view, all within our 10° range of distinct vision. At such a distance the camera does very well, because distance has already done what camera and geometrical perspective usually do.

The Relief Illusion

We look at a solid box, and we have no doubt as to which is the nearest corner; we have binocular vision to help us. Now look at Fig. 99. The corner marked *x*

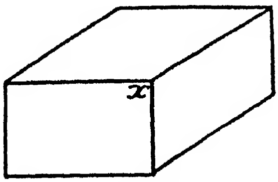


Fig. 99.

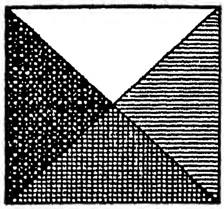


Fig. 100.

may seem to be the nearest corner; but look at the picture steadily, and it appears to be the farthest corner. With small efforts of the will we can see the corner *x* as either one or the other, nearest or farthest.

When we look at Fig. 100 we can see it as a flat surface divided into triangles, or as a pyramid, or as a pit. It is convenient to use the word *cameo* for the relief effect, and *intaglio* for the incised effect. When we turn a mask the right way up we have the cameo effect; upside down it gives the intaglio effect. When we look at the reverse side of a mask we normally do get the intaglio effect; but by concentrated attention we can see it as a cameo. It is said to be possible to see a bust as an

intaglio, though it is not easy to do so. No one seems to have succeeded in seeing the face as an intaglio; we are so thoroughly convinced of the outward curvature

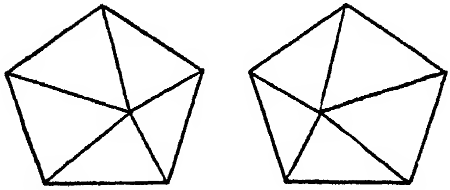


Fig. 101.

of the face that the brain refuses to perform the illusory trick of representing it as an intaglio.

We can get the confusion between cameo and intaglio quite readily with stereoscopic diagrams. Look steadily at the two pictures in Fig. 101. When the two coalesce we may see either a pyramid or a pit.

The Illusion of Slopes

A friend writes to me about an illusion of slopes: "I have been cycling over 'switchback' country. Every time I arrived at the top of a slope I was scared when I saw the next hill; it seemed to rise up steeply from the valley below. Very often the upward slope seemed to be fifty degrees or so; in fact my fears sometimes measured the slope as seventy degrees, and I quailed at the prospect of a long slow push. As I rode down into the valley I could see the slope before me; gradually it seemed to get more and more gentle. When I reached the bottom of the valley I laughed at myself and at my fears. I found myself faced with a slope of not more than fifteen degrees and quite possibly less. Can you tell me why I should get that exaggerated idea of the slope, not once only, but time after time?"

Few people can have failed to notice that illusion about slopes. A reasonable explanation of it seems to be our egocentric idea that our own environment is the normal; and added to this that level is normal. If the slope down which we are walking or riding is not too steep

we interpret it as level; if it is too steep for that, we interpret it as nearly level. In Fig. 102 a cyclist is shown riding down a slope with a similar upward slope in front of him. Below, the landscape has been tilted to represent the cyclist's illusion that the slope on which he is riding is actually level. The downward slope is thus added to the upward slope, and we get the appearance of a steep hill. To heighten the illusion, and the apparent steepness of the hill, we have to add something for overestimation of the height of the hill. We have to make a further addition, to wit, our tendency to overestimate difficulties, including the difficulty of riding up a very steep hill. With all these factors added together we get the mental effect illustrated in the lowest diagram.

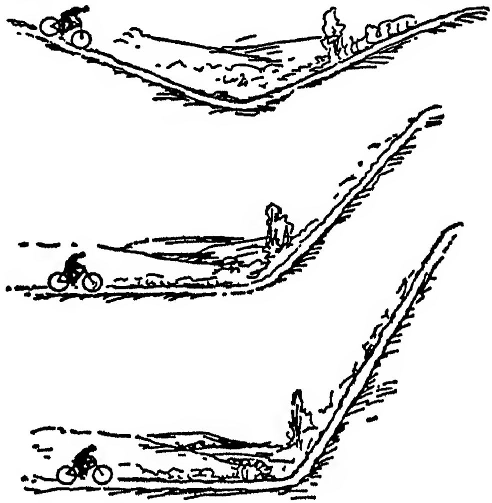


Fig. 102.

Model Mountains

There is no doubt that we do habitually exaggerate the upward slope of hills and mountains, especially when we are toiling up them. Even a steep mountain, like Snowdon, has a general slope of less than 30°; and on most mountains the general slope is even less. The fact that a mountain appears much steeper than it actually is, is probably due to the overestimation of its height. We have to add something, too, for the fact that cliffs and steep slopes draw the attention far more than gentle slopes; this helps to heighten the illusion of a very steep

slope. Fig. 103 shows the actual shape of a mountain, and the shape as it appears to be.

Mountains modelled to scale do not look like our ideas of what mountains should be; the slopes are far too

Fig. 103.

gentle. Men who make relief maps have to exaggerate the heights of their model mountains in order to give them steep slopes that fit in with our illusions, and make them look like our idea of mountains.

Irradiation

In Fig. 104 we have two small squares: a white square on a black background, and a black square on a white background. The small white square looks bigger than the small black square, although the two are exactly the same size. The black square seems compact, the white square diffuse; slightly, of course—the effects are not great. This is an illustration of the more general illusion that light-coloured surfaces appear to encroach on dark surfaces. On the left the small white square appears bigger than normal

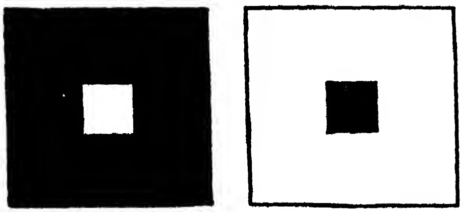


Fig. 104.

because it appears to encroach on the black background. On the right the white background seems to encroach on the small black square, and so reduces its apparent size.

The encroaching of light surfaces on dark is called *irradiation*. The explanation appears to be that the bright light from a light-coloured surface excites the nerve endings of part of the retina. The excitement spreads to adjacent parts of the retina, and so light-coloured surfaces appear bigger than they actually are when they are seen against a dark background.

In Fig. 105 we see again the lady who formerly went in for striped clothing; she has changed her ideas. On

Fig. 105.

Monday she was going to a committee meeting, where the background would be dark. She determined to throw her weight about, as we say: she decided to be large and flamboyant; so she wore loosely-fitting, light-coloured clothes. And she looked bigger than life-size; she encroached on her darker neighbours. The exuberance of her brightness and vitality increased the effect; it drew everyone's attention, and so again increased her apparent size. It was only by a grim exercise of his authority that the chairman prevented her from completely dominating the committee.

On Tuesday the same lady was going to a garden party, where the background of scenery and women's dresses would be light-coloured. Out of mere perversity, or per-

haps for some more subtle feminine reason, she decided to be slim. So of course she wore tight-fitting black clothes. She let the light-coloured environment encroach upon her, and so reduce her apparent size. And once more she was the observed of all observers (Fig. 106).

Indeed, when we want to look slim, black is the wear, and especially tight-fitting black. There was a lady who wanted to increase the apparent size of her head, which

Fig. 106.

happened to be rather small, so she wore tight-fitting black and threw a white shawl over her head.

When we look for them we are always coming across examples of irradiation; we meet them whenever dark and light surfaces come together. One of the best-known examples is " the old moon in the new moon's arms ". The bright crescent of the new moon appears to have a greater diameter than the part dimly lit by the earthshine, as anyone may see at new moon.

Irradiation may have something to do with the fact that the sun and moon look bigger when near the horizon than when they are high up in a clear sky, because near the horizon sun and moon are often seen in comparatively dark surroundings.

CAMOUFLAGE

(Try to answer these questions first)

How did colour-blind men detect camouflage?
What are the advantages of taking infra-red photographs from the air?
What is meant by "survival value"?
Why are dark and light races of the same animal sometimes found close together?
How do some animals change their colouring rapidly?
Which animals show seasonal changes?
What is countershading?
Why are many creatures dark above and light below?
What are disruptive patterns?
Why is it difficult for an airman to detect in which direction a camouflaged ship is heading?
How is movement camouflaged?
How are shadows camouflaged?
How does its web hide a spider?
Which animals advertise their identity?
Why was the camouflage of aeroplanes given up?
Which animals anticipated warlike weapons and methods?

CAMOUFLAGE is the art of creating optical illusions. There is something we want to hide, usually because we do not want an enemy to know what it is, or where it is, or even that it is there at all. We try to hide it by making it look like anything but what it is. If we succeed in

making it look like part of the background against which it might be seen, we have achieved a pretty good camouflage. Camouflaged animals look like all kinds of things. Some insects look like leaves, some like bits of stick; some mimic other insects; some caterpillars look like twigs; some moths look like the droppings of birds; larger animals are camouflaged to look like tall thick grasses amongst which they live. Animal camouflage is indeed often very elaborate and effective.

Early Camouflage

Artificial camouflage is a new art, at any rate as we practise it, and sometimes it is not very effective. It began to become important in the Four Years' War of 1914–1918. At first the art seemed easy enough, the sort of job that anyone with a brush and a tin of paint could undertake. We had, let us say, a big gun in the middle of a green field, and we wanted to keep its exact location to ourselves. All we had to do was to put a cover over the gun, and to paint the cover green, the same green as the grass all round it. Well, we did that, and thought ourselves hidden. An airman in a reconnaissance 'plane looked down; in our field he saw continuous green, and he missed the gun altogether. If the ground was sandy we used paint that was the colour of sand, so that the object appeared to be part of the sandy background. Indeed we were ready to imitate any kind of background, and it all seemed to be very clever.

What the Colour-blind saw

We had merely to get paint of the right colour, and we were all set for a successful camouflage; it appeared as if that was all there was to it. At first all went well, and then it began to appear that camouflage was not quite so simple as all that. A rather odd circumstance drew attention to one of the faults of the first attempts at

camouflage. It was found that colour-blind men were not easily deceived by it, and we had to know why. Well, the protective colouring was put on by men with normal eyes, and it was meant to deceive other men with normal eyes. It achieved its purpose well enough. But men with abnormal eyes were not deceived because they saw something different from what they were meant to see. We may have two yellows that look alike to normal eyes; and yet one may be a true spectrum yellow, whilst the other may be a mixture of colours which give yellow, say red and green; it may contain no spectrum yellow at all. If we suppress the red in the mixture, so that it looks black, then we get a colour which is not yellow at all, but a dark green. That is what happens to the colour-blind man, and that is why he is not deceived by this attempt at camouflage.

It was even proposed to employ colour-blind men to spot camouflage. And then it was seen that a colour filter would give normal eyes the effect of colour blindness. A colour filter that would let through all the visible rays except red would give normal eyes the effect of red-blindness, and so would enable them to detect camouflage. Then there were great developments in aerial photography. Sequences of pictures were taken in rapid succession, and these pictures were fitted together so as to give a continuous picture of a wide stretch of country. The photographs were taken through colour filters, and they were very effective in revealing places where camouflage had been attempted. Indeed, even without a colour filter, the camera has a very prying eye; it can show up things that are hidden from human eyes. Our eyes have a very narrow range of clear vision. We see a wide scene by letting our eyes range over it from point to point; and in ranging over the scene we may miss the very things we want most to see. We have to remember, too, that these things are the very ones that have been carefully hidden. The camera gives a clear and detailed picture over a much wider area, and of course a photograph can be examined point by point at leisure.

What Infra-red Rays reveal

To add to the troubles of the camouflage artist, photographs are now taken with infra-red rays. A camera used with infra-red plates has a very prying eye indeed. In the first place, the long infra-red rays are very penetrating, and the photographs show details even when the photographs are taken from a great height, and the atmosphere is not clear. And infra-red photographs show things that do not appear in ordinary photographs. We may imitate with great exactitude what the eyes see, and even what a photograph taken through a colour filter shows us; and the infra-red photograph gives us something utterly different. We may have two surfaces that reflect, more or less, the same visible rays, and yet they may react quite differently to infra-red rays; one may reflect infra-red rays, and the other may absorb them. The infra-red photograph shows the difference just as if it were a difference of colour or tone. It is as if we had two surfaces that both reflect blue light. One reflects blue light only, and so it appears blue. The other reflects red light also, and so it appears magenta. To normal eyes the two surfaces look quite different, though a red-blind man might see them not unlike each other.

Evidently it is not an easy task to camouflage efficiently. We have not merely to match colours to the naked eyes, but to match them also so that they give the same spectra. In addition to all this the two colours should reflect the same amounts of the same infra-red rays. The difficulty of matching infra-red is that these rays do not affect the sight, so that we have to rely on photographs for matching.

Survival Value of Camouflage

The object of camouflage is, we say, to create illusions; the more perfect the illusion the better the camouflage. But the illusion may be helpful without coming anywhere near perfection. We have a proverb which says that a poor excuse is better than none. We can accept the same idea about camouflage: a poor camouflage is

better than none. It is better for the gunner to have his gun concealed from human eyes, even though the camera reveals it, because it is easier to bomb a target which the bomber actually sees than one at whose position he can only guess. Everyone has seen the hover flies which look something like wasps; indeed many people mistake them for wasps (Fig. 107). When we observe them closely

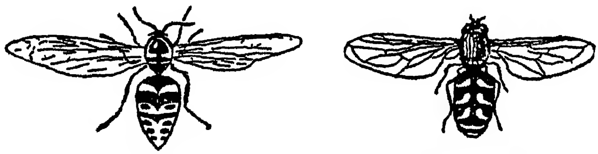


Fig. 107.

we see that the resemblance is not very great. They do not fly like wasps, or move their bodies like wasps; and though their bodies are banded like those of wasps, the resemblance is not close. Just the doubt, however, may save the hover fly from being preyed on, by causing it to be mistaken for a dangerous insect. Not every enemy will be deceived by the camouflage, but a great many will be, and especially those who are in a hurry. We say the camouflage has a *survival value*. The hover fly has a better chance of surviving and breeding other hover flies than if it did not bear some resemblance to a wasp.

Protective Colouring

The most obvious kind of camouflage is to imitate the colour of the background against which the object or animal may be seen. That is a very common kind of camouflage in animals; we call it *protective colouring*. It protects the animal, not necessarily from its enemies, but from observation. It is found in animals that prey on others as well as in those that are preyed upon. The tawny lion dwells on the fringes of a desert; its colouring imitates the sere vegetation and tawny surface of the

desert, so that it can creep up to its prey, or lie in wait for it, without being observed. It has at least a better chance of being unobserved than if it had a brilliantly coloured coat that showed up against the desert background.

The mouse is a small, weak animal that has no protection against its strong fierce enemies, including cats and owls. The coat of a "mouse-coloured" mouse protects it from observation, and so gives it a fair chance of surviving and breeding. A white mouse is far more obvious, and so it has little chance of surviving in a wild state. Indeed white mice only survive when they are artificially protected from their enemies.

Sometimes we find the same species of animal living in two regions that are close together but very different in appearance; one region may have rocks and soil that are dark in colour, whilst the other is light and sandy. There are two different backgrounds for the animals, and the coats of the animals show the same difference as the backgrounds: those living on the dark background are darker than those living on the light background. In each case the animals coloured most nearly like the background have the best chance of being unobserved and unmolested; they have a better chance of surviving and breeding. Generation after generation the animals least like the background are eliminated, whilst those most like it escape. Not all the like animals escape, and not all the unlike are eliminated before they have a chance to breed, but the survival value of likeness to the background is sufficient to produce a race of darker coloured animals in the dark-coloured region, and of lighter animals in the light-coloured region.

Quick-change Artists

The value of this kind of camouflage is so great that races of animals have developed with the power of changing their colouring when their background changes. The most famous example is the chameleon. There is a story of a soldier who experimented with a chameleon. He put it on red cloth, and it dutifully took on a red tinge;

then he tried it on green cloth and it turned green. Lastly he let it walk across a tartan. "It tried its 'ardest, but it was too much. The tartan broke its little 'eart. The pore little beggar just curled up an' died." There has indeed been a lot of exaggeration about the chameleon, but it does change with its background: at one time it is quite light in colour, and at another time dark.

Some animals can change colour in a fraction of a second, for example, certain species of fishes and lizards. The feathers of a bird and the fur of a mammal are not capable of such changes. The mechanism of the change seems to be something like this. The skin of the animal has two tinted layers, one usually darker than the other. The outer layer consists of coloured cells that can open out or close up. When they are open, the lower layer is almost completely hidden. When they are closed, the upper layer is hidden and the lower layer is exposed. Thus, by opening or closing the cells the animal can change rapidly from dark to light, and vice versa; it can adapt itself to its surroundings in a very short time.

Seasonal Changes

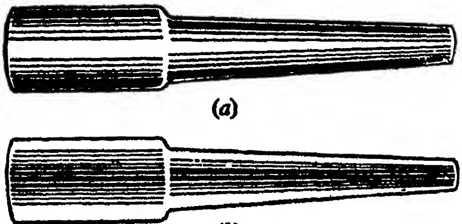
More lasting changes take place over much longer periods. Seasonal changes are fairly common. The greatest of the seasonal changes occur in countries where there are long severe winters with heavy falls of snow. The Arctic fox is snow-white in winter; it changes to a bluish-brown coat for the summer. The mountain hare changes from white in winter to brown in summer. Indeed white winter coats are a feature of the Arctic. Some animals, like the polar bear, wear white all the year round; others, like the reindeer and the moose, do not wear white at all. Perhaps they have little need for camouflage, or perhaps they just did not develop in that way.

These natural camouflage changes point to a weakness in artificial camouflage. The latter has only an accidental connection with its surroundings, and it does not change with them. Where there is vegetation there are likely to be seasonal changes, and good camouflage should follow them. The camouflage itself may change

by exposure to the weather, and these changes have little or no relation to the changes in the surroundings.

Shading and Countershading

Colour matching is an important part of camouflage, both in nature and in art, but it is not by any means the whole. In a painting the artist is creating illusions for us. Amongst these he gives us the illusion that objects depicted on his flat canvas are not flat but solid and rounded. He gets the effect by shading his colours. An evenly shaded surface looks flat, as flat as it actually is. A rounded surface has variations of light and shade, and it is these variations that reveal the rotundity of the surface. The artist copies these variations of light and shade, perhaps even exaggerates them, and so he creates the illusion that his flat surface is rounded, or hollow, or indeed any shape he wants. Shading is a very important part of the artist's technique.



(*a*)

(*b*)

Fig. 108.

The camouflage artist aims at creating a quite different set of illusions; he wants objects to look like almost anything but what they are. Following this idea, he often wants to make a rounded object look flat. He achieves his aim by what is called *countershading*. That is to say, he shades in reverse; he darkens where the object appears to be light, and lightens it where it appears to be dark. In Fig. 108*a* we have the barrel of a gun, looked down at from above as an airman would see it. The rounded appearance of the gun is suggested by the shading. In Fig. 108*b* a camouflage artist has been at work on the gun; he has put on the reversed tints of countershading, so that the barrel looks hollow. An observer, looking down from a plane, sees the natural shading of the gun, and also the countershading. If the latter has

been skilfully put on, the two kinds of shading exactly balance, so as to give an even tint. The rounded barrel has been made to look flat. If the tint also matches the tint of the background, there is an effective disguise. Countershading is not always so simple as that because most surfaces are not so regular as a gun-barrel. But the general method is the same : artificial light for natural dark, and artificial dark for natural light.

Dark above, Light below

Countershading is a very common device in the camouflage of animals. Animals are usually more strongly lighted from above than from below, so the lightest parts (so far as shading is concerned) are above, and the darkest parts below. So the countershading is light below and dark above. That is what we actually find in a great many animals. Everybody is familiar with the white belly of the rabbit, and most people have noticed how it shades off at the sides into the darker colour of the rest of the body. Most mammals are countershaded in the same way. Fishes are another familiar example; the countershading is dark above, shading off to white below. The countershading renders them all but invisible in the water. When a fish is sick, or dead, its belly turns up, and at once it becomes clearly visible. Sometimes a fish turns in a hurry and shows the underpart of its body as it does so. There is a sudden flash of light; but the flash is only momentary, and then the fish is again lost to sight.

Amongst our small animals the newt presents perhaps the most striking contrast between the upper and lower surfaces. A newt is not easy to see in the water because the upper surface is dull, and it is usually seen against the dark background of a pond. The belly is usually bright orange and yellow with shaded markings along the sides; and the belly is seen by water animals against the bright background of the water surface. Indeed all water animals are seen by other water animals against this background, so there is an added advantage in having the under part of the body white or brightly coloured.

Notice that when an animal is turned belly upwards, the countershading accentuates its rotundity, because in this position it imitates the natural shading due to light from the sun: light above, dark below. It is only when the animal is in its normal position that the shading becomes countershading and therefore a camouflage device.

Disruptive Patterns

We recognise objects very largely by their outlines. Imitative colouring helps to blend outlines with the background, and so to confuse an observer. Even a slight difference in tint between an object and its background may make it show up clearly. At night we recognise the outlines of houses and trees against the slightly lighter sky. If the background is much lighter than the object, the outline is even more readily recognised. The silhouette of a ship against the moon is distinctive; and an enemy at night manœuvres so as to get the ship between himself and the moon, so that the outline may show clearly. Artists often outline objects to make them stand out more clearly against the background; this device has the desired effect, even though the lines used in outlining do not exist in the actual object.

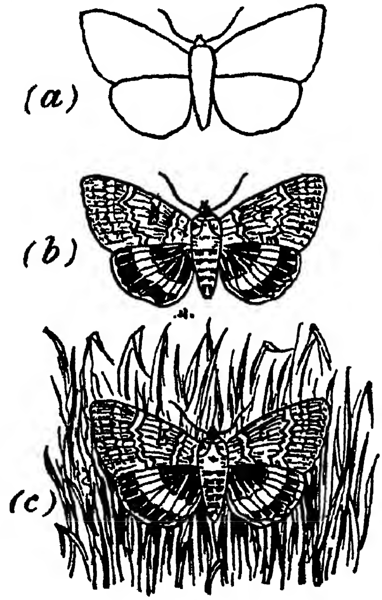


Fig. 109.

The camouflage artist tries to prevent recognition. He aims therefore at breaking up the outline that would facilitate easy recognition. One method is to use what

is called *disruptive colouring*. We paint the thing to be camouflaged with irregular bands of colour that run up to the edges of the outline, and so help to break it. Colours are sometimes chosen that match colours in the background, so that they may appear to join on and still further break the outline. Fig. 109 shows the familiar and easily recognised shape of a moth, the same shape with a disruptive pattern, and also against a dark background similar to the pattern. The outline of the moth is apparently changed by the background.

The Camouflage of Ships

The jazz patterns used as camouflage on ships are an example of disruptive colouring. A ship has a distinctive outline, whether it is seen in silhouette or from a reconnaissance plane above it. The object of the camouflage is to break up this distinctive outline, so that the ship may not be readily distinguished from the surrounding sea. The camouflage of ships is more effective than land camouflage for several reasons. In the first place it is not possible to take photographs, return to land, have them developed and printed, and then return to find the ship in the same position. Recognition depends upon human eyes, which are more fallible than infra-red photographs. The movements of the ever-changing seas help the camouflage by themselves helping to break the outline of the ship, and by providing a changing background, so that the eyes do not have fixed objects to use in ranging over the scene. The camouflage also helps to hide the direction in which the ship is moving. The reconnaissance plane is itself moving rapidly, perhaps at more than two hundred miles per hour, which gives the illusion that the sea is moving at the same speed in the opposite direction. The movements of waves also add to the confusion. In this mist of illusions there is the ship, camouflaged so that there is no telling bow from stern. It is little wonder that it is difficult to tell in which direction a camouflaged ship is sailing, in spite of the wake.

Zebra and Giraffe

Natural disruptive colouring is often much brighter than anything camouflage artists dare to attempt. The "football jersey" of the zebra is one of the most striking examples. At close range the zebra is an easily recognised animal; it has a distinctive outline and a very distinctive pattern on its coat. At a short distance it is almost invisible, especially against its natural background. The bright bars of the zebra's camouflage are almost everywhere at right angles to its outline, and they break up the outline very effectively. It is not necessary for the background to contain any features that closely resemble the stripes of the zebra. The point is that in looking towards a zebra we miss the familiar contour of the animal. Whatever we see, we do not see a zebra. Fig. 110 may remind us how sharply the zebra's markings run across the outline of the animal.

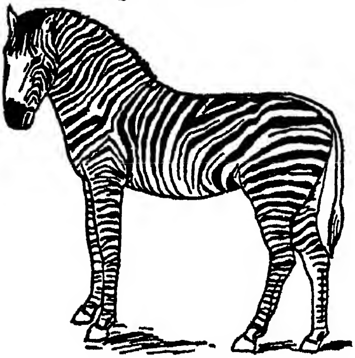


Fig. 110.

The bright pattern of the giraffe is another example of disruptive colouring. No one could mistake a giraffe at close quarters; but at a little distance, and against a background of trees, the pattern breaks the outline. The giraffe becomes invisible. Disruptive colouring that breaks easily recognised outlines is a very common device amongst moths and butterflies and other small animals.

Camouflaging Movement

Disruptive colouring is a protection for animals and objects that are at rest, and only to a lesser extent for things that are moving. As we have pointed out, ships are exceptional; they move amidst moving things, and especially amongst waves. Disruptive colouring is there-

fore to be found amongst animals that keep still as a protection, rather than amongst those that seek safety in flight. Stillness is indeed one of the most certain means of concealment. We can prove this by watching a butterfly. In flight it may be seen at a considerable distance. But the moment it is still it is lost to sight. We may know that it is quite close, perhaps only a few yards away, but it is invisible until it moves. Even very slight movements may be detected "out of the tail of the eye" as we say. Many wild animals seem to know this. They run at great speed for a short distance, and then conceal themselves by standing rigidly still against a suitable background. They do not, for example, stand so that they are silhouetted against a light sky; that would completely undo the effect of the disruptive colouring.

Army vehicles are camouflaged in much the same way as animals; that is, they are painted with disruptive patterns. But usually the camouflage artists are content with dull patterns; they do not use the brilliant colours that nature uses. They do, however, follow nature in using disruptive patterns to camouflage the vehicles when they are parked and not moving. It would be almost impossible to disguise the movement of lorries effectively. The movement itself renders them visible, and dust or splashing water adds to the effect. The camouflage of vehicles consists of patterns running more or less across them. If we want to camouflage them for

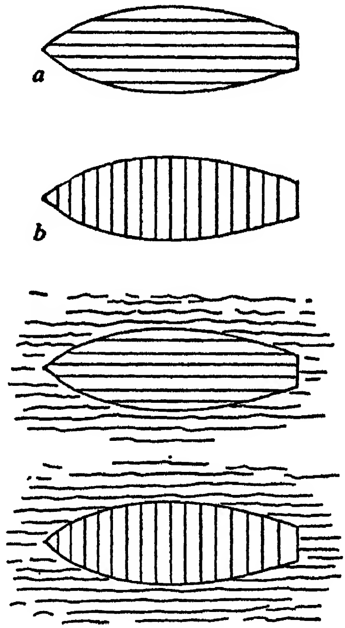


Fig. 111.

movement we want a different set of patterns; the lines of the patterns should run along the direction of movement. Lorries so disguised would be much more difficult to detect than those whose lines run across the direction of movement. A shape marked like *b* in Fig. 111 would be much more readily detected than *a*, if the two shapes were moving at equal speed toward the left. The difference would be even more noticeable if the background were lined in the direction of movement, as often happens in rivers. Fishes lined from head to tail have an added element that helps to render them invisible when they are swimming in a river.

Shadows ruin Camouflage

Cast shadows have a way of ruining camouflage completely. An artist may use countershading to paint a gun barrel so that it looks flat. He may break up the outline of the gun mounting with a disruptive pattern. And then the sun comes out and gives the whole show away. The shadow of the gun looks like a shadow of a gun, and like nothing else; the countershading and disruptive colouring have no effect on the shadow. Indeed the shadow is often the thing most readily seen; it stands out black against the background, and shows that there is something below that ought to be investigated. And people who want to be camouflaged do not like to have suspicious eyes turned on them, and suspicious people with cameras taking infra-red photographs of them.

Shadows are extremely difficult to get rid of, both in artificial and natural camouflage, partly because they are always changing as the sun moves across the sky. One method of abolishing them is to put a cover over the space where the shadow would fall. The method is simple enough, but it is not always easy to fit the cover into place. The wings of some moths have trailing fringes which bridge the gaps where shadows would come, and at least break them up.

Animals have other methods of getting over the shadow trouble. Many of them can, of course, run into shaded places where their shadows are lost in the prevailing

shadow. All they have to do is to run into the shade and stand still. Other animals, and especially young birds, squat down flatly, so as to reduce their shadows to a minimum, and perhaps eliminate them entirely. Some crabs scoop out depressions in the sand and lose their shadows by crouching down in them. But it is far from easy to get rid of shadows.

By the way, there is usually some shadow camouflage in the films; not of course in films taken out in the open, but in studio pictures. The actors do not usually squat down, or wear long trailing garments, or hide themselves in the shade; but shadows are cut out by lighting the scene from many sides, so that only unobservable traces are left.

The Spider's Web Camouflage

The next time you come across a conveniently placed spider's web look at it carefully, and look for one definite thing. First of all look through the web from the dark side towards the light. The web hardly seems to be there; it is all but invisible. That is the spider's point of view. It crouches behind the web and sees through it quite easily. Now look at the web from the point of view of the fly, that is, from the lighted side towards the dark. If the sun is shining on the web we see it clearly enough, but we do not see through it. Light reflected from the shining threads throws a veil over what is behind. The ever-ready spider is completely hidden. Spiders may secrete themselves in other ways, but the web is a good camouflage.

The spider's web has been imitated in artificial camouflage: we throw a net over the thing to be hidden. Netting is indeed an excellent camouflage. It has the great advantage that anyone behind it can see through it quite easily. We use the same kind of camouflage in offices and living-rooms. We put curtains or some kind of netting over the windows. We can see out well enough, but passers by cannot see in.

Advertising—the Reverse of Camouflage

The two classes of animals that need camouflage are

those that prey on other creatures, and those that are preyed on. The former want to be able to creep on their prey unobserved; the latter want to escape observation for very obvious reasons. The animals that serve as prey need camouflage more especially when they are weak, with no other means of defence. There are circumstances, however, when camouflage is hardly worth while; it may in fact be dangerous. Some animals are protected with spikes so effectively that they do not need to hide. It is an advantage to them to be recognised at once, so that possible marauders may be warned off. So far from resorting to camouflage, these animals advertise their identities. Others, like the skunk, protect themselves by ejecting an evil-smelling liquid. Here too it is an advantage to the animal to advertise its identity.

The camouflage of aeroplanes has been given up because the disabilities attached to it were judged to be greater than the advantages. The rough surface of the paint reduced the speed of the plane; it is said that the reduction was as much as twenty-five miles an hour in the case of some fast fighters. The additional speed was judged to be more valuable than any problematical protection given by the camouflage.

Animals Anticipate Man

It will have been seen that artificial camouflage follows very closely the various devices of natural camouflage used by animals. Indeed it is extraordinary how the devices used by men in war have been anticipated in the animal world. The swordfish anticipated the sword, and there are animals protected with spikes. The tortoise is an armoured car; the rhinoceros is a tank. The squid uses a smoke screen; the skunk uses the equivalent of poison gas; the bombardier beetle has a kind of artillery. Marching and battle formation are familiar amongst the driver ants. But men still look in vain for an aeroplane that can hover, fall like a thunderbolt, and take off again in a few yards.